ARCHIVES OF

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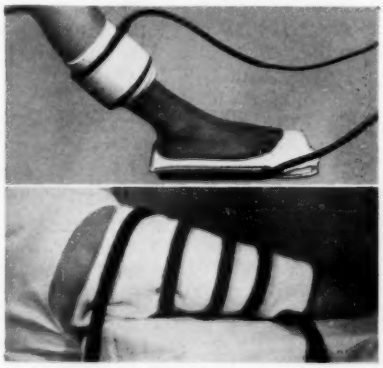

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Britton, Richard C.: Management of Peripheral Edema, Including Lymphedema of the Arm After Radical Mastectomy, Cleveland Clinic Quarterly, Vol. 26: No. 2, pp. 53-61, April, 1959.

Brush, Brock E.; Wylie, John H.; and Beninson, Joseph: Some Devices for the Management of Lymphedema of the Extremities, The Surgical Clinics of North America, Vol. 39: No. 6, pp. 1493-1498, December, 1959.

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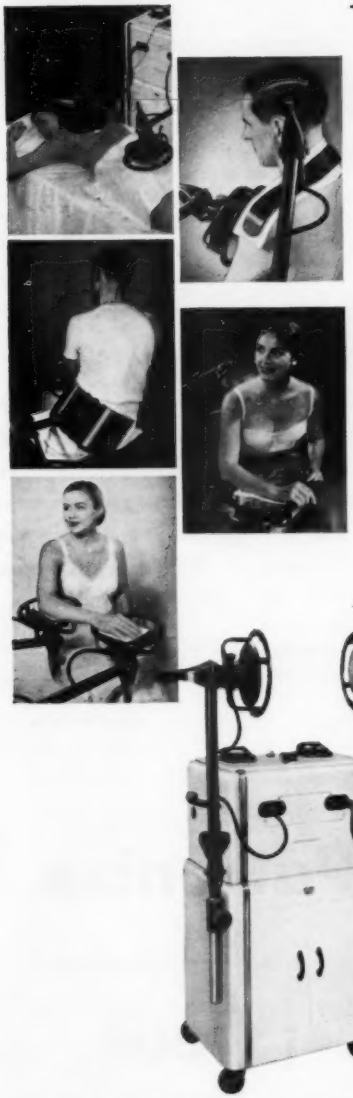

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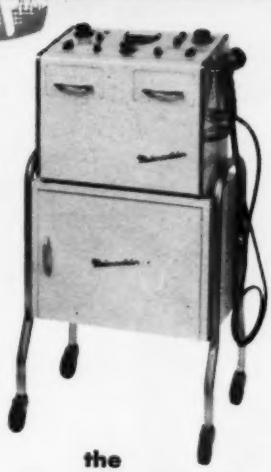

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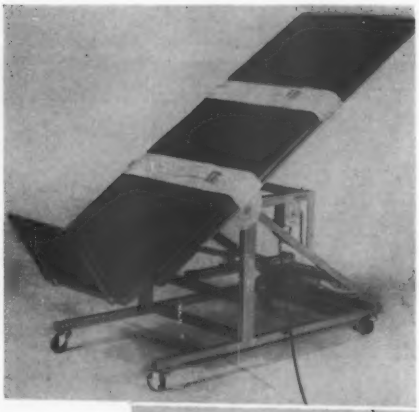

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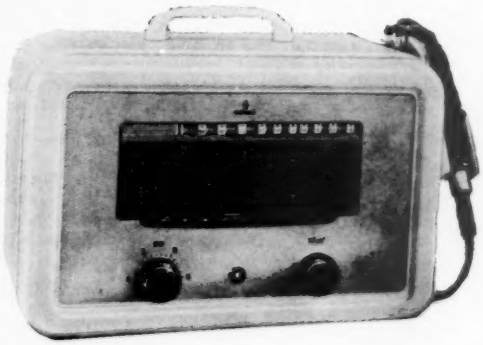

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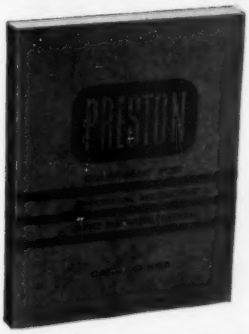

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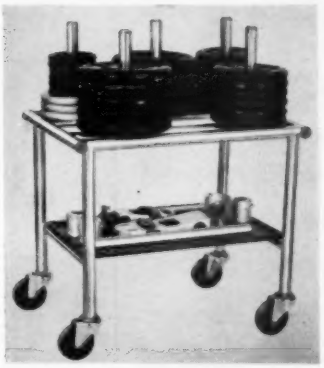

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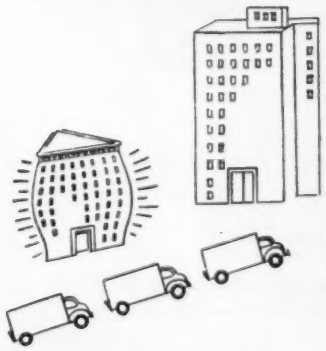

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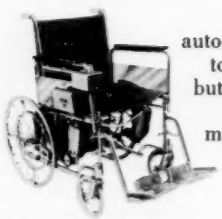

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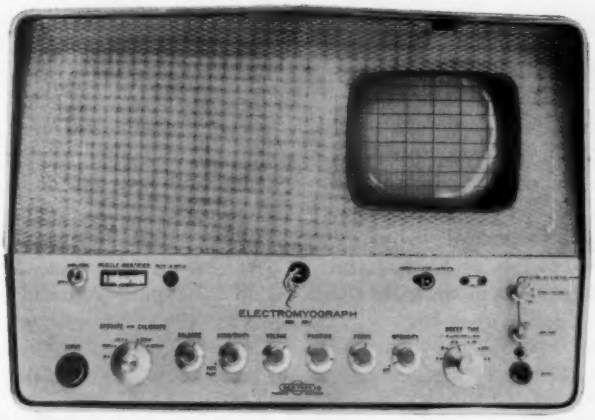

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Actually, leasing of buildings and equipment is getting to be a real answer to the problems of limited capital and high taxes . . . as seen, for instance, in the automobile lease, the real-estate lease, and even the leases on such items as electric brains and railroad cars. In fact, it is to meet these same capitalization problems that we have recently pioneered the first manufacturer's program for the leasing of medical electronic instruments.

According to Clay Williams, head of our Physical Medicine Department, we have several hundred Ultrasounds, Diathermies, Vibra-Baths and Muscle Stimulators now installed under our medical equipment lease plan. Leasing has evidently turned out to be extremely valuable to many institutions that have never before been able to "afford" a well-stocked physical therapy department.

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Use of Physical Therapy Modalities in the Treatment of Orthopedic and Neurologic Residuals in Hemophilia

Elizabeth Austin, M.D.
Ward Rolland, M.D.
and
Donna Clausen, R.P.T.
Los Angeles

● The genetic and hematologic facets of hemophilia are well documented and treatment of the commonly occurring orthopedic problems resulting from hemorrhage into the joints has usually been limited to bracing and rest. One year ago it was decided to use the routine physical therapy modalites of electrical stimulation, ultrasound, and specialized forms of exercise including rhythmical stabilization, stretching, and progressive resistance exercises to determine if the acute episodes could be shortened and result in less residual disabilities. In addition, a series of young patients with chronic contractures and prolonged atrophy were treated. It has been found that when certain obvious precautions are observed, ultrasound is effective in reducing the residuals of hemorrhage into the joints or other tissues. It is more efficacious than electrical stimulation used for the same purpose. Electrical stimulation, however, has been useful both in muscle reeducation as well as in the treatment of the peripheral nerve injuries which sometimes result from hemorrhage. The use of rhythmical stabilization exercises and progressive resistance exercises have resulted in increased power, greater stabilization about the joints with greater protection to them, and reduction of contractures. The supportive orthopedic care has been continued, but the treatment procedures have been of inestimable value to the patient and to his family, because for the first time he is being benefited by an active form of therapy.

Throughout history, the critical concern of physicians treating this hereditary disease has been preservation of life. With the advent of anti-hemophiliac plasma this consideration, while still important particularly when bleeding occurs internally, is overshadowed by the problems inherent in survival: bleeding into joints and muscles with resulting orthopedic and neuromuscular residuals.

Because surgery cannot always be used to manage these disabilities, the orthopedic consultant must select the more conservative and time-consuming procedures of bracing, rest, traction, and time. In recent years, more emphasis has been placed on the use of steroids in treatment of hemarthritic occurrences. Although all of these methods are helpful during the acute phase, they do little for the chronic residuals.

A unique opportunity to develop physical medicine treatment procedures to handle these residuals was presented by the fact that the Hemophilia Clinic in the California Hospital in Los Angeles is one of only a few similar centers in the United States, meeting the medical and orthopedic needs of more than 390 families, some with more than one hemophiliac child. Adult hemophiliacs also are cared for. Anti-hemophiliac plasma and hospitalization are available on an emergency basis for local residents as well as those from surrounding counties, and some patients come from other states for general supervision.

One year ago in addition to the traditional procedures of bed rest, ice packs, traction and/or splinting, a program of physical therapy for in-patients was begun in an attempt to manage acute problems of bleeding into joints and muscle tissue. It was hoped that some of the subsequent chronic problems could be partially alleviated or entirely prevented. This program has gradually expanded to include out-patients, and in the past 12 months 35 patients (age range three and one-half to 33 years) have been treated. Some have residuals from other disease entities: at least three have a history of poliomyelitis; one is a paraplegic with bowel and bladder incontinence; one is a known epileptic.

All but two of these patients had bleeding into one or both knees, either recently or remotely; many had elbow and ankle involvement. Hips and shoulders were rarely affected while hands and wrists were involved frequently. In all

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Staff Physical Therapist, California Hospital.

Read at the 3rd International Congress of Physical Medicine, Session on Arthritis, Washington, D. C., August 23, 1960.

but one case multiple hemarthritic history was available.

Bleeding into muscles, for example, the gastrocnemius, the muscles of the forearm, thigh muscles and even muscles of the back, is fairly common. In two patients, hemorrhage into forearm muscles produced Volkmann's contracture. In another bleeding into the hip area resulted in nerve root compression at the fourth and fifth lumbar vertebrae with subsequent paralysis of the quadriceps and sartorius and sensory loss.

Observation would indicate that denervation may occur from small episodes of bleeding into critical areas, such as the groin, more often than is recognized. This hemorrhage may not be as seriously regarded by the patient or his family as is bleeding into a more obvious area such as the knee. For this reason treatment may be delayed for several months until muscle weakness and loss of sensation become a distressing problem.

Simply put, bleeding into the joint produces pressure with pain, rapid atrophy of muscles associated with the joint, contractures with resulting deranged joint mechanism, changes in the synovia and joint cartilage, and osteoporosis.

While repeated intra-articular hemorrhage may lead to fibrosis of the synovia and contraction of the joint capsule, it appears that the advanced disorganization typical of hemophilic arthritis is the result of subchondral and intraosseous hemorrhage which accompanies the hemarthrosis. Bleeding into these sites produces erosion of joint cartilage and cavitation within the intra-articular portions of the bone. Hyperplastic synovium may contribute further to the damaging of cartilage about the joint margins. A most striking finding in younger patients is that of accelerated maturation and hypertrophy of the epiphyses adjacent to affected joints. It has been suggested that chronic hyperemia of the epiphyseal cartilage induced by continuous or recurring hemarthrosis is responsible for this change.

Repeated bleeding, beneath articular cartilage and into bone, leads to deformity and on occasion to fibrous ankylosis of the joint. The blood-distended joint causes pain and mechanical interference, leading to limitation of motion; this in turn aggravates the atrophy of bone and muscle just as it does in chronic joint disease from other causes. Extensive para-articular bleeding may occasionally be complicated by development of Volkmann's contracture.

Low grade fever is not uncommon during the acute hemorrhagic episode. Affected joints are swollen, warm, and tender at rest. When active or passive motion is attempted, the pain encourages the patient to restrict motion voluntarily until the doctor can restrict it mechanically.

Mild joint hemorrhage has a short course, and normal configuration and range of motion may be restored in a few days. When hemorrhage is more severe, or when the joint is reinjured before complete recovery, symptoms and findings persist for months and years.

Following repeated and/or severe hemarthrosis, the joint gradually deteriorates and bony enlargement, thickening of the capsule and adjacent soft tissues, and varying degrees of atrophy of muscle are found. The most common advanced lesion is flexion contracture of the knee accompanied by posterior subluxation of the tibia. In other cases there has been rigid fixation of a knee or ankle in complete extension.

Bleeding into muscles jeopardizes the blood and nerve supply locally or distally with the usual sequelae of atrophy and trophic changes. A calcified clot sometimes interferes with motion. Bony ankylosis is rarely seen, but fibrous ankylosis is not uncommon.

Physical medicine treatment was designed to use time honored procedures to treat the obvious orthopedic and neuromuscular disabilities with little regard for the hemophilia. Medical, orthopedic, and pediatric consultants provided close supervision.

Early resolution of hematomata is of critical importance. Toward this end both ultrasound and interrupted galvanism were used. Ultrasound was used with reservation early in the program. Total wattage was kept as low as one

watt total dosage with an 11.5 cm.^{2} transducer. It soon became abundantly clear that daily use on affected acute joints and muscles produced dramatic results. In an attempt to control results, ultrasound was used on some superficial bruises while others of about the same intensity and age on the same patient were used as untreated controls. In all cases the bruises treated with ultrasound resolved more rapidly than the controls. No adverse reaction to the treatment was ever noted.

Dosage of ultrasound now begins at .3 watt/cm.^{2} and is increased to .4 watt/cm.^{2} for two to three minutes. The usual coupling methods are used. In more serious cases plasma is usually given under the direction of the medical or pediatric consultants; thus the degree of effectiveness of ultrasound alone in the more serious hemorrhages cannot be ascertained. However, from the point of view of the patient and his parents ultrasound is given credit for more rapid absorption of the hematomata. The usual consideration is given to contraindications.

Interrupted galvanism did not prove to be as effective as the ultrasound and therefore only five patients were treated by this means.

Restoration of range of motion begins with preservation of as much range as possible during the acute episode of bleeding. Immobilization in the position of comfort or application of traction to the limb begins with admission to the hospital or with any home episode not requiring hospitalization. "Tennis shoe" traction using from three and one-half to seven pounds, or Buck's traction, is the type preferred. As joint pathology subsides motion may improve and produce immediate re-injury to the joint, particularly if the child is very young or especially active. In these cases, flexor muscles around the joint again go into spasm and more range of motion is lost. Well-padded posterior splints have proved effective in holding the correction obtained by traction and *gentle* manual stretching; these are changed frequently.

Many patients present multiple severe contractures as the result of old hemorrhages, prolonged bed rest, and limitation of activity. Contracture is present in nearly every instance of elbow hemorrhage. It is postulated that this is caused by continued use of the hands which precludes complete rest of elbow joints; the children lean on the elbows a great deal when confined to bed, and present methods of stretching elbow joints are not completely effective.

In the presence of a knee joint contracture, a hip flexion contracture is usual, and often bilateral hip flexion contractures are apparent. In approximately 50 per cent of the cases of knee flexion contracture, heel cord tightness is also observed. It is thought that this probably results from prolonged bed rest without proper foot support rather than from hemorrhage into calf muscles.

Restoration of range of motion in the presence of osteoporosis, marked muscle atrophy, weakness, and joint pathology is accomplished by gentle stretching, splinting as discussed, and judicious exercise.

If the contracture is old, and there is no evidence of acute bleeding in the area under treatment, heat in the form of hot packs is used in an effort to obtain relaxation of some of the tight structures.

Stretching is both active and passive. The child is first taught to recognize the difference between any slight discomfort related to stretching and true joint pain. Some adult member of the family is instructed in stretching exercises for a home program. No instance of bleeding is known to have resulted from gentle stretching to tolerance.

Restoration of power to atrophied muscles is an important factor in attempting to prevent recurrence of joint trauma. It is not always possible to determine clinically whether the marked atrophy is the result of joint pathology with disuse, or whether it is aggravated by denervation resulting from earlier hemorrhage into critical areas. Electromyography to make this distinction is not always desirable.

Electrical stimulation has been particularly effective in retraining muscles. It can be applied to muscles around a joint intimately involved in recent hemorrhage. A static type current has

been used for periods up to 30 minutes. In the presence of long-standing knee flexion contractures, electrical stimulation seems to help to reactivate quadriceps which are functioning far below normal.

As joint pathology subsides, gradual active motion is begun using static muscle contraction. The usual graded exercise program follows.

Powder boards, water, and gravity have been used as assistive agents. Hydrotherapy is particularly useful because there is little chance of injury, and underwater resistive exercise is used as a prelude to active exercise against gravity.

When resistance can be tolerated, manual resistance is always given, first so gently that when weights are finally used they begin at one and two pounds. If the patient is exercising an unbraced leg, the weight is applied proximal to the ankle joint. It is felt that weight in the form of the traditional quadriceps boot may lead to ankle hemorrhage even with the drop-foot attachment. This is especially important if a history of ankle hemorrhage is present.

A brace can be used for resistance in knee extension when the patient is able to lift the weight of the brace. A quadriceps boot has been used when it can be applied to a leg protected by a brace.

Standard dumbbell exercises are important if the child is a candidate for crutches. As a rule these patients are poor candidates for crutches if any other method of transportation and locomotion can be arranged. Damage to elbow joints is often traced to the use of crutches.

Protection of joints from trauma during ambulation is accomplished by the use of braces which are ordered by the orthopedist. As a joint recovers from a recent hemorrhage, weight-bearing may start for very short periods during the day with the brace locked in extension. As muscle power improves in the extremity with use and exercise, and if the joint shows no evidence of recurrence of hemorrhage, a program of walking with brace unlocked for increasing periods is begun and continued until ambulation without a brace is accomplished. This graded ambulation regimen may take months and even years. If severe damage has occurred in the past, many patients may never achieve brace-free ambulation. In these instances the realistic goal is ambulation in the brace with minimum deformity and without further hemorrhage.

Swimming is encouraged as both recreation and a therapeutic exercise. This is the only safe active sport in which the majority of these patients can engage without injury to joints and muscles.

Case Report 1

A seven-year-old boy injured his left wrist in a fall at school in late May, 1959, and presented a Volkmann's contracture with extensive median and ulnar nerve damage. The child was hospitalized for one month and received plasma. Extension of fingers was possible only with the wrist in 60 degrees of flexion. Treatment consisted of electrical stimulation (galvanic current initially) and active and cautious stretching exercises two times daily while hospitalized and three times weekly thereafter. Several passive splints were used to maintain correction in the position of function. Instruction for home exercises was given to his mother. By Oct. 15, 1959, the patient's left hand was completely functional, and in November he was learning to play an accordion.

Case Report 2

A 17-year-old boy shut the left arm in a door in May, 1959, with subsequent hemorrhage around the left elbow. Gradual loss of function of the left hand occurred. The patient was brought to the clinic two months following the injury with a moderately severe Volkmann's contracture. With the wrist in a functional position, no extension of fingers at the interphalangeal joints was possible. No opposition between thumb and fingers existed. Only 50 per cent forearm rotation was possible and the arm was held in a slightly pronated position due to fibrous ankylosis. Daily

treatment was begun with electrical stimulation and active and passive exercise. Passive splinting was used to maintain the position of function. Some gradual improvement was seen in hand function. No improvement has been seen in rotation of forearm. Hand function is now about 75 per cent of normal and maximum benefit has been achieved.

Case Report 3

A 30-year-old man with recent left knee joint involvement has had multiple hemorrhages. He became wheelchair bound in early 1955. The left knee joint showed narrowing of the joint space, irregular articular cortices, and subluxation of the tibia. The quadriceps was essentially non-functional and the patient handled the left leg as a flail extremity.

Daily treatment began October, 1959, with electrical stimulation followed by a slowly progressive active exercise program, which gradually changed as described in this study.

Electrical stimulation was discontinued when active motion against gravity was begun, and since then it has been used only when periodic episodes of fluid accumulation (which also occurred before treatment began) interfere with exercise. The intermittent synovitis has responded well to ultrasound and electrical stimulation.

Treatment included resistance exercises to the right leg to improve power prior to ambulation.

The patient started walking with a left long leg brace on March 1, 1960. He has had one episode of hemorrhage into the vastus lateralis which temporarily confined him to the wheelchair for seven days. Steroid therapy was instituted in March to aid in prevention of joint irritation which had occurred in the past when he attempted to walk.

Power in left quadriceps was 10 per cent in October, 1959, and 50 per cent in March, 1960. In July, 1960, he ambulated five days weekly with crutches and braces in a full time job. He was brace free two days weekly.

Case Report 4

This eight-year-old boy had severe knee and hip flexion contractures of three years' duration and could neither walk nor balance without the support of bilateral long leg braces.

Daily treatment consisted of active and passive stretching exercises with active and resistive exercises where applicable. Stretching was usually preceded by hot packs. Results are shown in table 1.

Table 1: Treatment Results

	July 30, 1959		Sept. 11, 1959	
Contractures	**Left**	**Right**	**Left**	**Right**
Knee	45°	30°	20°	10°
Hip	25°	20°	none	none
Power				
Quadriceps	25%	40%	50%	60%
	Not ambulatory		Is able to walk without braces for brief periods.	

Following hospitalization, treatment was given on an out-patient basis three times weekly until November, 1959. At that time the cost of transportation and mother's preoccupation with two other children, one of whom is a hemophiliac, reduced treatment to one time per week. Slight regression has been noted since the reduction in treatment.

Conclusions

Standard physical medicine treatment was used for the acute and chronic neuromuscular and orthopedic conditions and deformities occurring in 35 hemophiliac patients.

There appears to have been marked reduction of morbidity related to the recurring acute bleeding episodes, and there is promise that chronic weakness and deformity can be dealt with as well. Observation indicates that alleviation of weakness and deformity may result in fewer acute bleeding episodes.

Acknowledgment: The authors are grateful to Ellis W. Jones, M.D.; Madeleine Fallon, M.D.; Shelby Dietrich, M.D.; Shirley Whiteman, M.D., and Andon A. Andonian, M.D., for their assistance in preparing this study.

Quantitative Muscle Testing: Principles and Applications to Research and Clinical Services

Willis C. Beasley, Ph.D.
Bethesda, Md.

● Progress in many phases of physical medicine and rehabilitation depends directly upon discarding traditional subjective methods of evaluation and adopting experimentally verified, objective and quantitative procedures for evaluating the effects from various types of treatment on neuromuscular functioning. Over the past 15 years the author has conducted intensive research continuously in the field of quantitative muscle testing for the explicit purpose of developing and standardizing methods and of accumulating basic knowledge that is a necessary foundation for systematic clinical evaluations. In the application of all clinical norms, there are three essential requirements: (1) a standardized method of measurement so that different examiners can obtain comparable results, that the same examiner can rely upon repeated tests from time to time, and that disturbing spurious factors can be minimized; (2) a body of pertinent information on the average value and variance of the function in normal population groups, and (3) a standard method for evaluating the significance of a patient's deviation. Selected examples are used to show how contributions from this research specifically apply to clinical evaluation of muscular strength, fatigability, and response of muscles to passive stretch. For each of these three neuromuscular functions, some results will be reviewed from research directed toward developing quantitative normal reference values and criteria for computing deviations from normal. The necessity for adjusting norms in relation to age, sex, body weight and other anthropometric factors are illustrated by several examples. The broad application of these contributions is stressed, such as (a) methods for computing percentage level of paresis; (b) sensitive methods for detecting changes in strength level as a result of treatment; (c) criteria for normal and abnormal rates of fatigability and (d) criteria for normal and abnormal response of neuromuscular systems to passive stretch of muscles.

Progress in many phases of physical medicine and rehabilitation depends upon developing and utilizing objective and quantitative procedures for evaluating the effects from various types of treatment on those phases of neuromuscular functioning that are made evident in the magnitude and patterns of muscular contraction. Over the past 15 years, I have conducted intensive research continuously in the field of quantitative muscle testing to fulfill the requirements of a broad and comprehensive program, which was formulated in 1945.

Three of the specific objectives in this program discussed in this paper are the following: a. to develop and standardize useful instrumentation and methodology as required by the complex problems as encountered; b. to acquire basic knowledge on the behavior features of muscular responses that necessitate normal reference values as a foundation for systematic clinical evaluations; and c. to obtain the necessary quantity of measurements on samples of subjects from both normal and pathologic population groups for the purpose of developing useful normal reference values and a means of identifying and computing values for abnormal deviations. Other objectives of the original program have been described.[1, 2] Currently, the research has been extended to a study of minimal strength requirements in relation to occupations and to the development of a disability rating system based upon physical impairment of muscular strength and endurance in repetitive effort.

This paper supplies a brief review on some of the characteristics of an adaptable system of instrumentation that permits measuring and recording many important features of integrative neuromuscular action through the associated effects in muscular responses; it describes the approaches that are being employed in research on both the normal and abnormal aspects of strength levels revealed in the patterns of contraction as depicted by the recorded variation in force level as a function of time, fatigability, myotatic responses, and reciprocal innervation through the correlated reversal of tension between antagonistic muscle groups; and, finally, this paper illustrates by specific examples from extensive data how measurements

Director, Biophysics Research Laboratory, Bethesda, Md.; Director, Kinesiology Laboratory, Elizabeth Kenny Institute, Minneapolis.

The basic program of research is being aided currently by a grant from the Sister Elizabeth Kenny Foundation, Minneapolis. The special project on minimal strength requirements in relation to occupations is being aided by a grant from the Office of Vocational Rehabilitation, Department of Health, Education and Welfare. Earlier research was supported and aided from several additional sources: The Division of Public Health Methods, U. S. Public Health Service, in which the author held the permanent appointment of Biophysicist (1944-54); The National Foundation for Infantile Paralysis (1945-51); Division of Research Grants, National Institute for Neurological Diseases and Blindness (Grant B-565); and the Gustavus and Louise Pfeiffer Research Foundation. Indirect benefits were derived from grants to the Department of Physical Education, Yale University, by the Pope Foundation and the Grant Foundation.

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of maximum force levels on normal subjects and postpoliomyelitis patients for the muscle systems involved in hip extension, knee extension, and ankle plantar flexion have been applied to development of simple methods for computing percentage level of paresis relative to average expectation in normal population groups. Examples are discussed on the application of these statistical norms to interpretation of clinical and epidemiologic estimation of paresis resulting from poliomyelitis.

Reference is made in the title and throughout this paper to application of this research in clinical services. As a matter of clarification, the term "clinical" when used here refers to the type of service that is becoming more and more general in progressive physical medicine clinics. Rather typical of this kind of clinic, and the associated facilities for quantitative evaluation of physical impairment, and for determining amounts of improvement in neuromuscular functions in response to treatment, is the description given by M. K. Newman[3] of services utilized at the Lafayette Clinic in Detroit. I do not refer to the more classical and popular meaning, such as that employed by Wartenberg,[4] who defines clinical diagnostic tests as those "which can be performed easily in the office or at the bedside and without recourse to any laboratory procedure." Many of the instruments and physical equipment items that are used routinely today by physiatrists in their clinical services were regarded, a few years ago, as useful only for "research" purposes. The change from "research" to "clinical" of a methodology depends primarily upon demonstration of its usefulness in helping the clinician to solve the problems he encounters. Moreover, it is evident in the literature that the discovery and conception of what problems exist, and decisions on which ones should be included in physiatrics, are flexible and alterable considerations, depending largely upon the progress made through appropriate research. In physical medicine, the trend is conspicuously toward more accurate, objective, quantitative and diversified methodology. Simplicity is necessarily a secondary consideration, since higher priority must be given always to the requirements of adequacy. Accelerated progress in medical knowledge on the management of disease and physical impairment not only derives from, but also stimulates still further, invention and development of new and better instrumentation and equipment. Prospects, therefore, are definitely in the direction of sequentially greater complexity in all phases of the clinical armamentarium. This evident trend will, undoubtedly, nourish the growth of a more adequately trained ancillary corps of medical technologists with rigorous professional qualifications and with correspondingly elevated status.

Functional Aspects of the Basic Instrumentation

Basic instrumentation and accessory equipment employed in this research were invented and developed by Beasley at the National Institutes of Health (Bethesda, Md.) over the period from 1944 to 1954. Improvements required in some phases of the research have been made in more recent years. Detailed description of this instrumentation, accessory equipment, and examples of methodology have been published.[1] Only brief mention is made here on those functions of the instrumentation that serve to clarify applications to research problems and resulting clinical services.

The total instrumentation is called an electronic myodynagraph, and the methods employed in muscle testing with this instrumentation are referred to as electronic myodynagraph methods. The electronic circuits have a variety of simplified controls, which facilitate procedures in the muscle testing activities. For example, the electronic myodynagraph provides panel controls for an electronic or secondary calibration recheck for the particular tensiometer in use. There are six scale ranges, which are applicable to each tensiometer, in the ratios 0.1 : 0.2 : 0.5 : 1.0 : 2.0 : and 5.0. One may switch quickly from one scale to another, depending upon the force levels encountered in a testing situation. Both manual switch and automatic relay control of the tape

recorder are provided to start and stop, respectively, the recording at the beginning and end of each trial. The automatic relaying is set to function at eight per cent of full scale on any scale, regardless of sensitivity. Separate amplifier gain controls permit equalizing full scale deflection of the needle on a large meter and the writing stylus on the tape recorder. The meter may be used at any required distance from the electronic myodynagraph and recorder, thereby providing a visual indicator to the subject being tested for special purposes.

Several types of force-sensing load cells (tensiometers) are employed in association with the electronic myodynagraph recorder. The active elements in the tensiometer are Baldwin wire strain gages (type SR-4 or ABD-11, 120 ohm). The most sensitive tensiometer of recent design weighs 0.07 pound (32 g.) and has a useful range in measuring tensive force from 0.01 pound (4.5 g.) to 200 pounds (91 kg.). A less sensitive tensiometer weighs 0.21 pound (95 g.) and has a useful range in measuring tensive force from 1.0 pound (0.45 kg.) to 3,000 pounds (1,360 kg.). Because these tensiometers are so sensitive, light in weight, remain linear in response to a wide range of tensive force, and can be connected entirely within the axis of a movable tension cable, they are adaptable to many measurement situations in muscle testing that, otherwise, would not be possible.

These units are called *axial tensiometer gages*. When they are coupled directly in a tension line and move in unison with the axis of the connecting cable, the tensive force acts also along the central axis of the axial tensiometer gages. This force is recorded graphically as a variation in force with respect to time. In mechanics, this relationship defines an "impulse," that is, the integral of force with respect to the time over which the force acts. In accordance with Newton's Second Law of Motion, the effect of the "impulse" (Ft) in imparting change in velocity (momentum) of a mass is proportional both to the amount of force and the time during which it acts. In application to the recording of muscular forces, one discrete impulse from start to finish is called a "tensive impulse." A unit tracing for one tensive impulse is referred to as the tensive impulse curve. The tensive impulse becomes a basic unit of measurement. Integration of the area of the tensive impulse curve provides a correlative measure of muscular energy expended in contraction and, likewise, the effectiveness of the contraction in producing motion of external loads. This dual conception of the mechanical and biophysical significance of the tensive impulse unit of measurement leads to further interpretation of relationships between abnormal patterns of muscular tensive forces and their reduced efficiency in imparting motion and momentum to external masses. This aspect of my reasoning and related research is being treated in a separate paper.

In use, the axial tensiometer gages are coupled directly to the patient's extremity or body segment and to one end of a tension cable, permitting the measurement and recording of both active and passive muscular force reactions. Resultant tension on the axial tensiometer gages necessarily follows Newton's Third Law of Motion on the equality between active and reactive force. The total tension in the external cable system, which is usually connected at a right angle, or nearly so, to the central axis of the extremity, may be regarded as the active force. There is no significance attached as to which direction is called "active" or "reactive," since the reference is relative. Provisions in every measurement situation, however, must assure that the external source of applied or active force is always capable of exceeding the maximum reactive force of the muscle system.

Requirements for Norms

The following discussion on requirements for norms assumes that we are seeking objective and quantitative norms. These principles are not intended in any sense to be applied to "subjective impressionism," which dominates most of the current practice, and which can never be regarded as competing with the principles of objective science.

Throughout all clinical procedure where practice requires an evaluation regarding the "normality" of a patient's process or function, the criteria establishing this right must be derived necessarily from information on non-clinical normal population groups with respect to the function evaluated. When the function is found to vary significantly with age, sex, race, or other factors, appropriate corrections of the norm or standard of reference must be made. This view is consistent with the philosophy set forth by Sunderman and Boerner[5] in their excellent encyclopedia of normal values now in general use clinically. Compatible ideas on this important consideration have been expressed by Kendall and Kendall[6] in their commendable and practical discussion on the clinical implications of the term "normal" in relation to muscle (strength) testing. The Kendalls do not employ quantitative methodology, but their views on the meaning of normal are pertinent.

In the process of acquiring, establishing and applying any norm, whether clinical or otherwise, the following principles are essential in the methodology:

1. *Objectivity.* Above all else, the methods must be fully communicable and transferrable from one observer to another. In some fields, such as quantitative muscle testing, this may involve extensive teaching and training, depending upon the simplicity or complexity of the required knowledge. An essential prerequisite to attaining objectivity is instrumentation. Whenever possible, instruments having appropriate precision and permanent recording features must replace impressions, judgments, and other subjective evaluations. The recorded event must be quantitative. Instrumentation must have, of course, its own basic constancy of performance and calibration controls. Automation should be carried as far as facilities permit. This does *not* mean that we can eliminate the required human intelligence and skill, both being indispensable in controlling the instruments, the procedures, and all phases of the methodology. This does mean that even though we have quantitative instrumentation, we can *not* turn the whole methodology over to a technician and expect a fully objective transfer to occur. Finally, another indispensable prerequisite in establishing objectivity is a complete enumeration of the factors that must be controlled and exactly how this must be done in practice. Otherwise, a second observer may fail to duplicate completely the essential procedures of the first observer. In application to quantitative muscle testing, these principles mean that personnel engaged in such testing must be *more* highly qualified and *more* thoroughly trained than is customary among those engaged only in the procedures of manual muscle testing. We can attain objective and valid quantitative tests only by attending to the indispensable functions of the examiner in controlling instrumentation and other vital phases of the methodology.

2. *Validity.* The object or process subject to measurement must be clearly and unambiguously defined, and the methods employed must measure demonstrably this object or process unequivocally. Most arguments about methodology (the desirable and instructive kind) center around this question of validity. Are we measuring what we say we are? What criteria have we formulated to test the validity of our method? These questions must be answered impartially and critically. For instance, in quantitative muscle testing, we are obliged to dispose of the presumption that we can measure tensive forces of individual muscles. That is impossible in the living, intact organism. Our kinesiologic principles must be fully attuned to what occurs in integrative action under the conditions of testing, in order that we may fulfill the requirements of validity in our concepts of what we are measuring in a particular procedure.

3. *Standardization.* The method employed in establishing normal values must be duplicated in all *essential* respects when a rating for an individual case is to be based upon an adopted normal reference. This means that all of the requirements under objectivity and validity must be observed. This principle is as necessary in muscle testing as it is in biochemistry, physics, or any other precise

determination. We can not arbitrarily standardize a procedure from armchair reasoning. We must go to the laboratory and find out what works best, then standardize from objective comparisons. Without such empirical standardization, we shall never achieve an essential requirement for quantitative norms.

A major complicating factor in quantitative muscle testing is that for many muscular actions the positioning and other controls that are most valid for normal subjects do not apply or can not be used so effectively for some patients. In such circumstances, we may develop the rating for a patient by using different positioning, providing the method gives a valid test for the patient. The first seven years of investigation on this program involved in fact thousands of comparative experimental studies for the purpose of acquiring knowledge as a basis for selecting comparable and valid procedures for the purpose of rational standardization of methodology.

We can not review such a complex set of considerations here, but only emphasize the principle that one can not proceed to standardization without such comprehensive determination of effects on measurements from varying the procedure. From these determinations, we then select and identify the controls that are most relevant for the requirements of objectivity and validity. This has been done, and the informative results are being methodically prepared for an instructive manual on methodology in quantitative muscle testing for all important muscular actions with which clinicians are concerned.

4. *Reliability.* When the combined requirements for objectivity, validity and standardization are fulfilled precisely in practice, the methodology has maximum reliability. The variance of the function that is measured may then be interpreted as a characteristic of the function. There is much misuse and misinterpretation of this term "reliability." For example, the test-retest correlations between measurements made on the same individuals on the same day (or different days) are employed rather routinely as a measure of reliability of the "test." The concept involved is ambiguous. When such correlations are "low" (say, less than 0.80) the test is said to be "unreliable." When the correlations are "high" (say, 0.95 or more) the reliability of the test is said to be "satisfactory." This reasoning assumes that the function to be measured is a constant, and if our measurements do not repeat exactly, nor with small variance, the fault is said to reside in the test. In some of the basic sciences this assumption of constancy is justifiable in some instances, but even then may not be generalized uncritically.

When test-retest correlations in excess of 0.95 are obtained, it is quite likely in most instances that the methodology has been controlled and that the function measured has a relatively small variance in individuals over the period of time spanned between test and retest. However, this conclusion does not always follow necessarily from the fact of the high value for test-retest correlation. Both in quantitative muscle testing and in other laboratory measurement situations, I have encountered circumstances where an *invalid* test yielded high values of test-retest correlations, but when corrections in method were made to improve validity, the "reliability" correlation coefficient was reduced grossly. The invalidity arose from measuring an extraneous factor that was constant, whereas the function, which was intended as the object of measurement, had much larger inherent variance. By "extraneous" here I mean only that the item measured was not the item intended. I have noted many similar examples in the literature on research in muscle testing, where the investigator reported exceptionally high test-retest correlations, and the source of invalidity through measuring an extraneous factor was clearly in evidence. Thus, a low value of test-retest correlation does not indicate *per se* that the methodology is at fault. The function itself may have relatively high variance that is independent of the methodology.

As applied to quantitative muscle testing, in relation to either carefully controlled research or to clinical evaluations of a patient's condition and progressive changes, this assumption of

constant function is erroneous. In many kinds of neuromuscular disorders, variability from time to time is an inherent characteristic. Sometimes the variance is so apparent that it is revealed by clinical examination, and may be interpreted as malingering. To interpret such conditions correctly, we must be able to distinguish between the failure to control methodology from the inherent or occasional variability of the function. It is of primary importance to know the source of variance; otherwise, important conclusions even from refined methodology may be wholly erroneous. The observer must be hypercritical at all times on the control of the methods employed. When variability in measurements are suspect, confirmation must be achieved through repetition of the measurements, and sometimes through devising rather "tricky" variation in methodology. Additional study of the person should be pursued also, to ascertain whether events intervening between tests may have influenced the measurements obtained.

5. *Statistics.* In the process of deriving quantitative norms for the purpose of evaluating deviations from "normal," the selection and application of appropriate statistical treatment of data is a rigorous *sine qua non.* A mass of data, even with computations of averages and standard deviations, does not constitute the elements of statistical methodology that must be employed in traversing the gap from the original data to the final inferences, conclusions, and new laws relating to the processes that are the primary subject-matter in quantitative muscle testing.[7] Eventually, the full significance of my meaning here will be in evidence. A representative example is given in the last section of this paper. Statistics is one of the basic, indispensable components in the technic of scientific methodology, just as logic and epistemology form the framework within which our reasoning operates. In developing and applying norms to any process of nature, physical or biologic, we are obliged to draw upon these disciplines in full measure to achieve enduring conclusions.

An elementary essential in developing norms for quantitative muscle testing is a thorough knowledge of the average value and variance of the functions in the populations to which the norms will be applied. This means that we must sample non-clinical normal populations adequately by age, sex, and other features in order to draw conclusions as to expected values for each of the functions among these partitioned groups. It is necessary to analyze data of this nature in an exploratory manner, in order to discover trends that may lead to generalizations. We may find from this exploratory analysis that the sampling up to a certain point is inadequate or leads us to suspect biased trends. So we are obliged to sample further, and study possible sources of bias, and subsequently control or eliminate them. On the basis of experience in this program up to now, we may expect sometimes to find simple laws through a mass of data that give us a direct basis for interpreting normality, and deviations therefrom, in application to wide ranges in the age and physical type of individuals. In other instances, perhaps we shall not be so fortunate. But the first step, unavoidably, is to conduct the exploration in accordance with the most dependable rules of statistical technology.

6. *Medical Significance.* After scientifically valid norms have been acquired in accordance with the principles set forth above, the final stage of application to clinical evaluation of a patient requires the physician's contribution. In order that this phase of the program may develop useful and medically sound criteria, the clinician must contribute information. We need to know in respect to each function the amount of deviation from the adopted normal reference that must be in evidence before the departure is regarded medically as symptomatic of a condition that is significant, in the sense that some type of treatment or rehabilitative program is indicated at varying levels of urgency and prognostic outlook for benefits to the patient. This body of information can be accumulated only under circumstances where quantitative methodology is being applied continuously to patients, and where the

correlated clinical diagnosis, treatment and progress of the patient are being studied concurrently in relation to the quantitative evaluations.

Biomechanical Factors in the Standardized Methodology

We can not measure tensive forces of muscles in direct alignment with the axis of contraction but, instead, must measure the resultant forces as applied by groups of muscles against skeletal segments. Consequently, a large number of problems arise in standardizing procedures, because of the great variety of biomechanical designs involved in the numerous joint structures and their associated motions. Among others, Steindler[8] has given especially helpful and suggestive schematic analyses on some of these considerations. During the first five years in this research program, detailed experimental studies on the following more important factors were carried out, because of their direct application to the practical aspects of testing procedures and their significant influence on quantitative results: a. the influence of general body position (supine, prone, sitting, standing) with other features of posture and technic equated as nearly as possible; b. variation of force in relation to the angle between the tension cable axis and the central axis of the extremity (the standard adopted is a right angle, and the force reaction obtained when this angle is used, was named the *tangent force reaction*); c. the relationship between the tangent force reaction and the position of the skeletal segment in the natural arc of motion (this involves influence from changing initial length of the muscles on contractile force developed, as well as the influence on the tangent force reaction from mechanical design of the skeletal joint structures); d. variation in force and torque as related to distance on segment from joint center (lever length); and e. influence of controlled counterpoise through employing mechanical assists such as strapping, blocking, wedging, etc., to the areas of the body where stresses were found to be excessive, and sometimes painful, even though the primary muscular action under test was producing force well below the maximum obtained when mechanical assists were in use. These experimental studies provided the necessary factual background for developing standardized positioning that is based upon a knowledge of how much influence each specific factor has on quantitative results.

Methods Applied to Four Modalities of Neuromuscular Behavior

Regardless of whether we are estimating normality, and deviations therefrom, in reference to muscular strength, fatigability, myotatic forces, or reversal of tension between antagonistic muscle groups, the inference of deviation from normal requires a criterion of normality and a method for computing deviations from the norm in standardized units. Measurements that can be treated statistically for such purposes are being collected continuously for each of these four neuromuscular behaviors. To accomplish useful clinical application, it is necessary in addition to accumulate quantitative data, by the same methods, on patients whose diagnoses are available for study.

Eventually, then, we shall be able to make meaningful statements quantitatively on *how much* weakness a patient has; *how much* a patient's fatigability deviates from an expected normal amount; *how much* and what kind of spasticity is revealed; and *how much* impairment in ability to reverse tension between antagonistic muscle groups exists. If we can measure accurately how much exists at a given time, we can also then measure *changes* resulting from progress of a disease or improvement due to any form of treatment, providing we accompany the determinations with properly designed experimental controls. By this means we acquire a powerful methodology not only for experimental research, for example, on the effects of new drugs in reducing spasticity or other forms of involuntary tensions, but also as an adjunct to clinical diagnosis where usual methods may not be sufficiently sensitive or convincing. That these four

types of behavior enter into diagnosis and differentiation of neuromuscular diseases conspicuously often is clearly indicated by DeJong[9] in his thorough presentation of factors in the neurologic examination. From experience to date, we may expect that in some instances the use of quantitative procedures will provide assistance to early diagnosis in advance of usual clinical detection.

For purposes of illustration, we shall review briefly some technical features of the methodology as applied to each of these four neuromuscular behaviors, with indications of normal and abnormal features of the tensive impulse curves. The materials presented are intended to be suggestive of further potential applications by those concerned with such processes in their research and practice.

1. *Muscular Strength.* The term "strength" as it is commonly used in the literature is broadly generic, and refers to a wide variety of measurement or testing situations. About the only common denominator among these references is *amount* of force or resistance, regardless of how it is measured or tested. In my electronic myodynagraph methods, we can distinguish between *maximum instantaneous tension* attained in a trial, the *average tension* for the whole trial, or any other significant feature of the tensive impulse curve that is presented. In many instances, the distinction between the maximum instantaneous tension and the average tension is highly significant. When maximum indicators only are used in strength testing, such as the spring balance as used originally by Lovett and Martin,[10] the airplane cable tensiometer as applied to muscle testing by Clarke,[11] or a myometer developed by Neuman,[12] or other similar devices, we can measure only the maximum instantaneous tension, and hence other valuable features of motor behavior revealed by the tensive impulse curve are not available for analysis and evaluation.

Normal muscular contraction as controlled by voluntary effort is recorded as a tensive impulse curve with a broad flat top throughout the trial period, which is usually timed by metronome at 5, 10 or 15 seconds. The rise time at the start from zero to maximum is typically 0.2 to 0.4 seconds. This varies according to the mass of muscles involved and the maximum force level attained, but seldom exceeds the range indicated. Relaxation at the end of the trial is more rapid, requiring less than 0.1 second. When stabilizers, fixators, synergists and prime movers are all cooperating normally, and proper mechanical counterpoise for the body and the tested segment is provided, the plateau of the tensive impulse curve throughout the trial is remarkably straight for about 30 per cent of normal adolescent and adult subjects. In this instance, the value for the maximum instantaneous tension and the average tension are equal. For another 50 per cent of normal subjects, the plateau is very nearly a straight line, but drifts downward during a 10-second trial from the initial maximum to a terminal level five to 15 per cent less. The curves for normal children are typically not as steady as those for adolescents and adults. When the action is tested near the completion of the arc, with muscles in their shortened position, the tensive impulse curve typically is less steady and there is more reduction from initial to terminal points of the trial. In this range of the arc, there is also greater likelihood of muscle "cramps" or knotty spasm to develop. For both reasons in standardized testing, we used the mid-range (or beyond) portion of the arc. We always use the average value as the representative "strength" for a tensive impulse trial.

Some of the more significant deviations from a normal tensive impulse curve are shown by: a. lower maximum (or average) level attained in a trial relative to norms for the action and type of subject (paresis); b. variations of small or large magnitude above and below a fairly straight average value without significant negative slope (tremors, clonus); c. rapid or slow descent to lower values from initial maximum (relative fatigability); d. attainment of maximum level delayed to the end of the trial, rather than at the start (retarded recruitment of motor units in contraction, or sustained opposing tension in antagonistic

muscles that gradually relax); e. conspicuous irregularities of tension level with no definite mean level apparent (frequent in some forms of spasticity); and f. rapid descent from initial maximum to zero within two or three seconds without recovery in a 10-second trial (typical in some forms of muscular dystrophy).

The tensive impulse curves (fig. 1) illustrate a normal level of force (curve A) in trunk flexion maintained throughout a 10-second trial, with a minor tremor. Another subject (curve B) attained essentially the same maximum level, but revealed a rapid fatigue response. The average value of the impulse (average tension) for subject WKR was approximately twice that for subject WCA. The two forms of behavior were repeated typically in sequences of tests on the same day and on different days. A dynamometer that indicates only maximum level attained in the trial shows essentially equal strength for the two subjects. In weight raising tests, for the same muscular action and test position, WKR raised a maximum load of 78 pounds three inches from the floor, whereas WCA raised only 32 pounds. This illustrates a relationship between the average tension value and the ability to raise a weight load. The maximum value (maximum instantaneous tension) is not a valid predictor of weight lifting. The average tension value obviously provides a better measure of effective muscular strength.

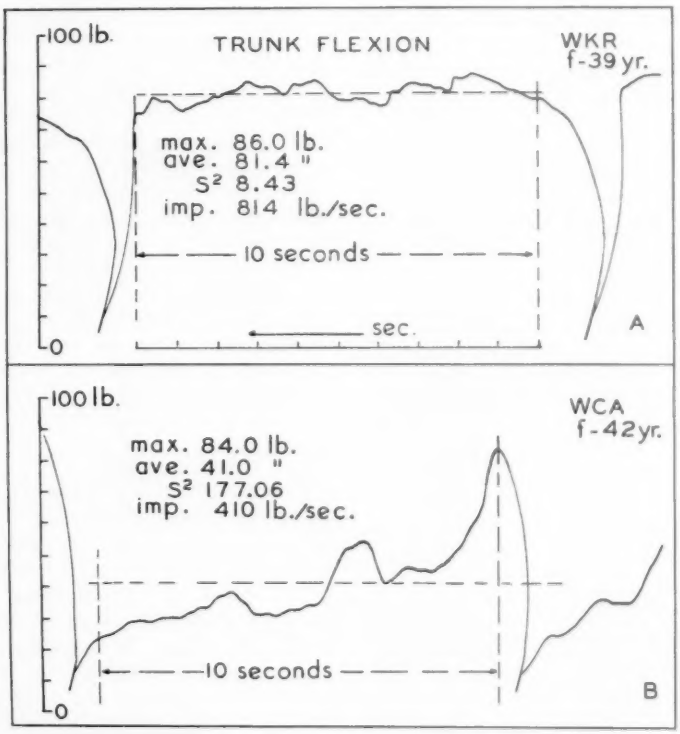

Fig. 1 — Examples of two ten-second impulse recordings, illustrating markedly different abilities of two subjects (adult women) to maintain maximum force level, even though the actual maximum levels attained during the 10 seconds were approximately equal. A mechanical dynamometer, which indicates only the maximum level attained, shows equal strength for these two subjects. Subject B fatigues more rapidly than subject A during a single trial and, likewise, during a series of trials. A single-trial recording of 15 to 20 seconds' duration provides a reliable and easily attained index to fatigability. The statistics shown for each subject are based upon readings of 50 force levels at 0.2 second intervals for each curve.

2. *Fatigability.* One hesitates even to mention this highly complex problem in a brief discussion. A particularly lucid and thorough analysis of the many physiologic processes involved in the different meanings of this term has been given by Karpovich.[13] We may raise the question for contemplation, at least, whether the exhaustion type of fatigue testing, such as that employed by Hellebrandt, Skowland and Kelso,[14] and by Clarke,[15] or by Cureton[16] in general physical fitness evaluation, is the most germane approach to identifying and measuring the kind of fatigability referred to when we characterize, for example, a form of muscular dystrophy as showing rapid fatigability, especially since this clinical observation is based upon two or three effort trials in a manual examination. We may quantify this latter type of fatigue quite readily by requiring a patient to exert maximum effort for three to five successive 10-second trials, and compare the tensive impulse curves obtained with those for normal subjects measured in the same manner, and evaluate deviations accordingly. This is a simplified approach, but appears to be appropriate to the kind of evaluation sought in the diagnosis of neurologic diseases.

We are not restricted to this simplified technic in our study of fatigue by electronic myodynagraph methods. In this phase of the program, we are continuing the collection of measurements by a variety of methods, varying the length of unit trials, duration of rest pauses between trials, and the total number of successive trials, even to the so-called exhaustion state. The objective is to acquire norms for simple, moderate, and arduous rounds of trials. By this means, we may find a more direct estimation of the kind of fatigue that is most closely related to performance in occupational tasks.

One advantage of this methodology is that all trials are recorded in sequence and timing controls are registered automatically on the tapes. Assuming that the tensive impulse integral is a correlative measure of the energy expended in contraction, summation of the tensive impulse trials gives a quantitative measure of this factor. In each trial all of the tensive force produced is recorded, and there is no loss in the measurement of this factor, as there is usually with the ergographic approach. Possibly from these studies we shall have a system of norms that will provide a practical basis for evaluating different kinds of fatigability, much in the same manner that we are now evaluating levels of paresis.

3. *Myotatic Response.* Reaction of muscles to stretch produced by externally applied force is recorded as a rise in the tensive impulse curve synchronously with the application of the active stretching force. This rise or increment in the tensive impulse curve is called the *myotatic impulse.* Examples of tensive impulse curves with superimposed myotatic impulse, together with further explanation of the methodology, have been published.[1, 2] A variety of controls is required, so that the incremental or additive muscular tensive force resulting from excitation of the stretch reflex system can be differentiated from the passive forces attributable to elasticity and plasticity of the muscles, and likewise may be distinguished from initial primary tensions due to either involuntary contraction (such as occurs in spasticity) or to the intentionally maintained voluntary tension that is present when the stretching force is applied. There are obviously numerous mechanical and biomechanical factors that must be accounted for in the methodology. A satisfactory explanation of these complex factors can not be included here. The required controls relate not only to mechanical arrangements in a particular trial, but also to comparative experiments that give the background information needed to interpret particular individual trials.

With the electronic myodynagraph methods, numerous arrangements can be employed to investigate and demonstrate normal and abnormal features of the myotatic responses. The additive tensive force produced in muscle systems under isometric conditions, when the customary percussion type of stretch is applied to a tendon, is recorded easily. Factors that influence the magnitude of response to

this transient stretch may be compared with the response obtained with sustained stretch, which provides a more effective stimulus to the myotatic sensory nerve endings (muscle spindles and tendon organs). The influence of initial tone and initial tension, in the muscles to which stretch is applied, on the magnitude of the myotatic response is a basic problem for quantitation, and has been investigated extensively in this program. In regard to this general problem, we need at present to develop a simplified, practical instrumentation that provides for parallel recording of the tensive force and the electromyographic response in the muscles, and the latter should be as fully quantitative as possible. Suggestive examples of the applications of such dual recordings in studying both normal and abnormal myotatic responses are given by Wright.[17] Some instructive experimental demonstrations of electromyographic responses under conditions of manually applied stretching were reported by Watkins.[18] With proper dual recording, some elements of ambiguity in certain phases of my electronic myodynagraph methods as applied to the myotatic response will be removed, and the conclusions that are now based upon secondary experimental controls may be validated by direct indications.

In order to interpret abnormal deviations of the myotatic response in neurologic diseases, especially different manifestations of spasticity, we need extensive information on the magnitude of the myotatic response of normal muscle systems, in relation to varied amounts of voluntary tension present when stretch is applied. A standardized experimental procedure was devised to collect normative data on this function. The normal subject controls the level of voluntary contraction by observing a visual indicator (large faced meter) that is correlated with the muscular tensive force produced. The stretching force is applied at predetermined levels of contraction, presented in randomized order, over the whole range from essentially zero initial tension to the maximum tension level a given subject can produce. From this information we then develop basic functional relationship between initial tension and myotatic response in normal neuromuscular systems. In the analysis of this information, the objective is to develop statistical norms for the myotatic response of different muscle systems that are usually emphasized in neurologic diagnosis. We may then compare the myotatic response obtained from stretching muscles that present initial involuntary tensions (as in spasticity), and arrive at quantitative evaluation of spasticity. Once this is achieved, we have a basis for evaluating effects from chemotherapy and other forms of treatment, and give quantitative estimations of changes relative to the pretreatment condition. We may estimate, as well, amount of change and the direction relative to normal expectation.

4. *Reciprocal Tension.* Because the whole process of reciprocal innervation and resulting alternation of tension between antagonistic pairs of muscle systems are of direct importance in neurologic diagnosis and treatment, methods were devised whereby some of the abnormal behaviors can be recorded and subjected to quantitative treatment. The same methods applied to normal subjects provide information on the expected normal behavior, as with the other modalities we have considered.

In studying the behavior of reciprocal tension, an extremity is connected by means of a rigid, padded cuff, within the straight axis of a tension line. One side of the tension line includes an axial tensiometer. The other section includes an expansion spring in which the tension is varied by a turnbuckle. The ends of the tension cable are fixed for recording reversal of tension under essentially isometric conditions. They are made movable by running them through a pulley system at each end, with adjustable springs or weight loads attached appropriately at either end beyond the pulley system. This allows reversal of motion and a means of recording passive resistance to stretch alternately between antagonistic movements. In either arrangement, reversal in the direction and amount of tension can be recorded. Both

procedures are useful in the study of spasticity.

The recordings (fig. 2) illustrate the behavior under isometric conditions for reversal of tension in elbow flexion and extension for a patient (10-year-old girl) diagnosed as spastic quadriplegia. The cable tension was adjusted to be well in excess of the patient's ability to produce muscular tensive force. The electronic balance was then set on the electronic myodynagraph to record zero active tension at midline on the tape. Active tension in extension and flexion are recorded as deflections in opposite directions from the neutral, zero line. Marked paresis is shown by this patient for both extension and flexion. At a slow rate of alternation (recording A), the patient could reverse tension in a fairly regular manner, each cycle requiring about six seconds. When the patient attempted reversals in response to metronome beats at the rate of 40 a minute (recording B), inability to reverse tensions from flexion to extension developed and only the flexor system produced active tension. The patient reported that with the faster rate she could not "think" fast enough to produce force in the direction of extension. This example suggests how the methods are employed in studying this function, of which there are a multitude of variations in research and clinical applications.

Useful normal reference data for this function are being accumulated. Methods employed involve varying the rate of reversal from one that is sufficiently slow to permit the subject to attain maximum force level in either direction, to a rate sufficiently fast that only one-half or less of the slow-rate maximum force is attained in the first few trials of a series. The number of trials in a series, performed in timed sequence, is varied from a minimum of five up to 100 or more on different days, in order to reveal the effects from fatigue on the control of reciprocal innervation and tension. The norms developed from these studies may be used then for quantitative estimates of abnormal deviations and treatment effects.

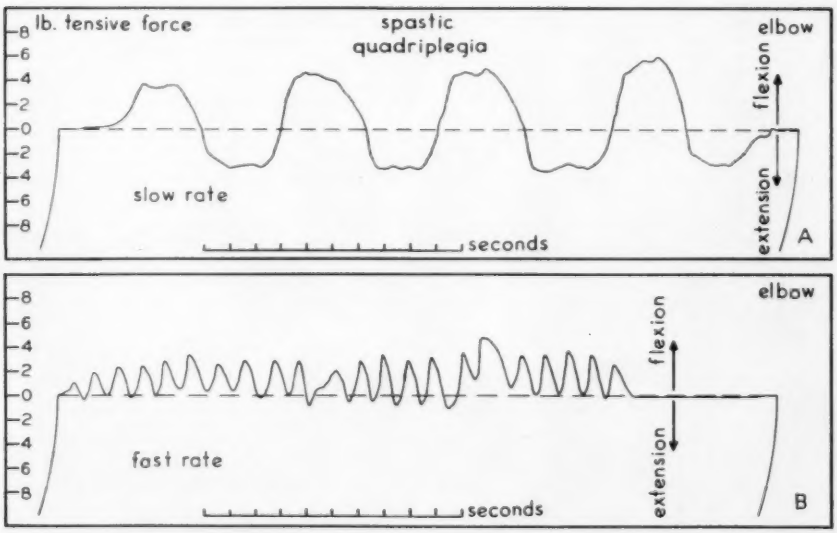

Fig. 2 — One example of a method for studying the process of reciprocal innervation by recording alternation of tensive force, almost isometrically, in a patient diagnosed as spastic quadriplegia. At a slow rate, this patient could alternate tension in the flexors and extensors of the elbow, even though the force level revealed marked weakness. At a faster rate, extension was inhibited and the unidirectional force level attained in flexion was reduced significantly. Variations of the method used here have many applications to research problems and clinical demonstrations concerned with spasticity in neuromuscular function.

Statistical Norms for Three Muscle Systems

Specialists in physical medicine and rehabilitation are faced continuously with the problem of estimating the presence and amount of paresis resulting from disease and trauma in varying forms. Such evaluations must be made on occasion for patients of either sex, at any age, and from all walks of life. The idea of paresis implies significant deviation from an adopted reference norm. It is necessary, therefore, that we have a quantitative criterion of normality, and a method for computing amount of departure therefrom in standardized units, in reference to any muscle system we are evaluating. Corrections of the norm, when necessary, must be made in relation to age, sex, body build, and possibly habitual occupation. Appropriate analysis must reveal whether and when such corrections are relevant. Consequently, research must be directed toward large scale investigations, properly designed and executed in accordance with the requirements for quantitative norms as described earlier in this paper.

In this research program there has been persistent endeavor to collect and analyze such data, with the above objectives in mind, on some 38 principal muscular actions that are traditionally included in clinical muscle testing procedures. There are many broad gaps in the required data at the present time for various age and sex groups. Prior to 1950 all of these muscular actions were studied experimentally in a variety of ways so that rational selection of methods for standardization could be made. Since 1951, however, data for the normal reference values on all actions have been obtained by using standardized methods.

Fig. 3 — One of the many variations of method employed in measuring the forces produced by muscles participating in the hip extension action. The axial tensiometer gage is fastened to a T-bar on the top frame. Weight of the chain and cuff are balanced out electronically. Gravitational component force of the leg, in this gravity assisting position, is recorded first, and the net muscular effort force is read independently. Firm counter-pressure by the broad pelvic strap reduces stress on muscles of the lumbar area during maximum effort.

Consequently, as we accumulate enough measurements on each action for satisfactory statistical treatment, all of the data can be used. It is necessary to analyze these measurements in a variety of ways, in order to discover simplified statistical procedure for computing norms that are easily applied to individuals. The original data, of course, will become a useful reference catalog of measurements when adequate sampling has been completed.

The data collected for some muscular actions have been reduced to reference norms that are exceptionally easy to use in practice. We shall consider here the final results from extensive data collected over a period of approximately nine years for the muscle systems involved in the three actions hip extension, knee extension, and ankle plantar flexion (or ankle extension, as some prefer). Three detailed papers have been prepared for publication, one for each of these actions.[19-21] These papers give the full details on methodology, sources of data, original force measurements, and other adequate statistical treatment. In the present discussion we shall give attention only to the final results of the statistical analysis as they relate to devising normal reference values.

Methods. The illustration (fig. 3) shows one standard method of measuring the force of hip extension, with the leg tested at 45 degree hip flexion, and the other leg counterpoised at full extension of the hip. Here, force is measured in the gravity assisting direction. In another standard method for this action, the subject is positioned prone lying, with both legs projecting beyond the end of the table. The nontested leg with full extension at the hip is supported on an extension frame. The tested leg is positioned at 45 degree hip flexion, and force is measured in the gravity opposing direction. The gravitational component force of the leg is measured and subtracted for the gravity assisting position, and added for the gravity opposing position. In either position, the tensive impulse curve was recorded for a 10-second trial three times for right and left, with the cuff placed near the ankle joint. The average value for each tensive impulse curve was employed as the measure of "strength." Data for both methods are included in the normal distributions considered here. Methods employed for knee extension and for ankle plantar flexion have been published.[2, 7] The reader is referred to those sources for further details.

Ratio Statistic: force/body weight. As blocks of data are accumulated for normal subjects in various age and sex groups, a planned set of tallies on relationships between force measurements, age, sex, body weight, height, ratio body weight/height, and ratio force/body weight are maintained for study and appraisal. For these three muscular actions, and some others as well, a remarkable trend was apparent for the ratio force/body weight. All of the groups of data, classified separately by single year age intervals from five to 30 years, and by sex, tended to cluster around a constant mean value that was characteristic but different for each of these three actions. The distributions appeared to represent Gaussian forms, so trial computations and tests were made. As the samples of data increased in size, the approximations to this model improved.

Consistency in the average value for this ratio for each action appeared to continue throughout the age range from five to 29 years. Beyond 30 years the trend is downward, and appears to be a negative linear slope as a first approximation. Tentatively, then, for all measurements on individuals between the ages of five and 29 years, and for both sexes, the ratios force/body weight were summed into three frequency distributions, one for each of the three muscular actions under consideration. The statistics for these distributions are given in table 1.

Samples. The first line of table 1 gives the number of subjects (N_s) in each sample. The groups for hip extension (1,610 subjects) and for knee extension (1,364 subjects) have satisfactory sampling of children, both sexes, from five through 12 years of age; males 19 to 24 years; and females 24 to 29

Table 1: Statistics from Distributions of the Ratio Force/Body Weight Computed for Individual Subjects (Normal Reference Groups)

Statistic Combined Groups Normal Subjects 5-29 Years	Hip Extension	Knee Extension	Ankle Plantar Flexion
Subjects, Ns	1,610	1,364	2,359
Measurements, Nm	9,660	8,184	9,436
Measurements, Nd	3,220	2,728	4,718
Average Ratio force/body weight, x	0.6192	0.9792	2,4107
Estimate of μ (99% confidence interval)			
Lu	0.6232	0.9853	2.4231
Ll	0.6152	0.9731	2.3983
Standard deviation, S	0.0892	0.1242	0.3295
Relative variance, RV%	14.41	12.68	13.67
Transformation factor, Tx (to %N scale)	161.499	102.125	41.482
Goodness of fit			
χ^2	29.69	27.39	25.58
df	22	22	34
p	<0.145 >0.119	<0.211 >0.176	<0.869 >0.836
Transformed values (Tx × statistic)			
x	100.00	100.00	100.00
Lu	100.65	100.62	100.52
Ll	99.35	99.38	99.48
S	14.41	12.68	13.67

Nd used for Lu and Ll; RV% = 100 S/x

p from Pearson & Hartley,[23] probability integral for χ^2

years. There are no subjects in the range 13 to 18 years, either sex; only a few males 25 to 29 years, and only a few females 19 to 24 years. As opportunity permits, sampling of the missing and deficient age and sex groups will be supplied and new estimates made. Tabular details on these samples are given in the papers referred to previously.[19-21] Because the trend was so definite for the ratio force/body weight throughout these two samples, preparation of the statistical treatment given in table 1 was regarded as justifiable. The sample for ankle plantar flexion (2,359 subjects) is highly satisfactory. Each single year is represented from five to 29 years, male and female. The sample sizes by single years, and sex separately, range from 39 minimum to 64 maximum. All subjects in each of the three major samples had a negative history with reference to poliomyelitis, orthopedic defects, and all other neurologic diseases that usually are regarded as inducing muscular weakness and related neuromuscular dysfunction. This is the sense in which these groups are characterized as "normal."

As a matter of historical interest, and contrast in scientific methodology, Martin[22] reported a high correlation ($r = 0.93$ males, 0.86 females) between body weight and total strength in the age range from five to 18 years. For "total strength" he used the sum of scores for 21 muscle systems on each subject. His conclusion is quoted often in the literature as proving this fundamental relationship. His sample, however, could not be regarded as having provided the basis for proving anything about a normal trend. He had a total of 240 subjects (128 male and 112 female); 168 had a history of acute poliomyelitis, and many of them had serious orthopedic defects, such as club foot and scoliosis. Some gave obvious indications of malnourishment. In the range from 12 to 18 years, some single year groups are represented by only one or two subjects, and the maximum number was six. Yet the author states, "The group of subjects as a whole was fairly representative." This is the best example I have ever encountered in the literature of what a sample purported to represent a normal trend should *not* be! Our requirements in statistical sampling have changed conspicuously since 1918.

Measurements, N_m, N_d. For individual subjects in the hip extension and knee extension samples, three measure-

ments each on the right and left sides were recorded and are listed as N_m in table 1. For ankle plantar flexion, two measurements each right and left were recorded. For all three samples, one average value each for right and left, listed as N_d, was tallied in the distributions from which the statistics and estimates of population parameters are derived.

Sample Statistics and Parameters. The essential distribution statistics of interest here are the sample sizes N_d, the arithmetic means x, and the standard deviations *S* of the distributions.* The numerical values as given in table 1 were used in all computations. To simplify the discussion at times, we shall round off the exact values to approximate ones. Values for x give the expected, average value for the ratio force/body weight. Values for *S*, for samples as large as N_d, may be regarded as estimates of σ, the unknown universe standard deviation. From these values, 99 per cent confidence intervals for estimates of the universe parameter μ were computed in the usual manner, and the limits are listed as Lu and Ll in the table. When we interpret the reliability of x from estimates of μ, we assume randomness of the samples and that the values for the ratio force/body weight are distributed in the universe as a Gaussian function. We can not say, rigorously, that the samples are random. They are "catch as catch can." Nor do we assume bias, where none is known to exist. We are obliged practically to make an *operational assumption* that statistics of our samples do not differ significantly from those that would have been obtained, if the method had employed strictly random procedure. This assumption is necessarily tentative, but can remain operational until positive evidence of bias is revealed. We shall test the assumption regarding a Gaussian function.

NB: As a matter of printer's expediency, the lower case x (10 pt) is used throughout this paper to denote the sample arithmetic mean for a distribution of individual values of the ratio force/-body weight, and is to be considered a substitute for the conventional "ex-bar". All other symbols follow general standards. Each item of statistical notation is defined clearly in the text.

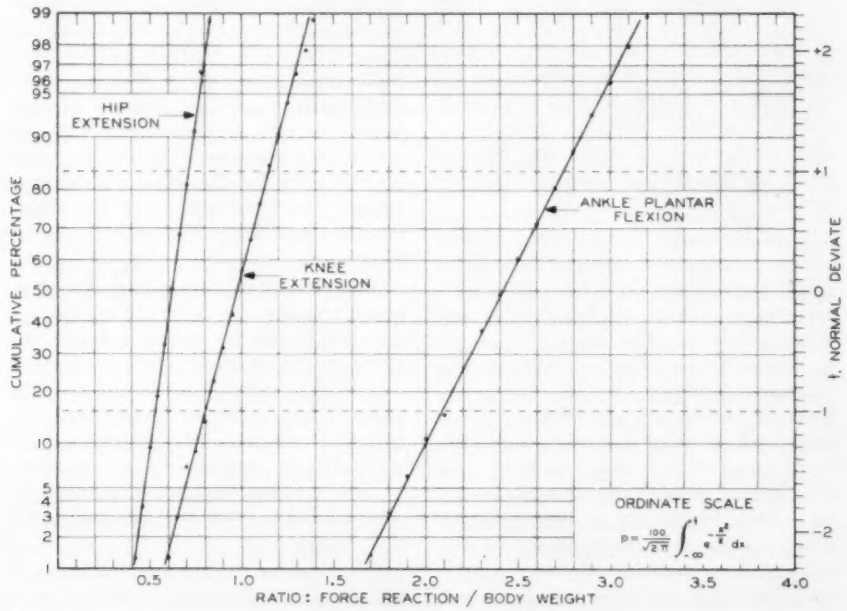

Fig. 4 — Relationship between the ratio force/body weight (abscissa scale) and the distribution of measurements (ordinate scale) on normal subjects from five to 29 years of age for the three muscle systems employed in hip extension, knee extension and ankle plantar flexion. The ordinate scale is computed by the equation shown on the graph, so that a Gaussian or "normal frequency" distribution plots as a straight line. The chi-square tests for "goodness of fit" of these curves are given in table 1.

Goodness of Fit. Two methods are employed here to test whether we are justified in assuming that the ratio force/body weight is distributed as a Gaussian or normal probability function. A graphic method (fig. 4) illustrates that all three of these distributions approach a Gaussian curve quite closely. The vertical ordinate grid for this chart was drawn on a graph sheet with 500 mm. divisions. Each line is located within 1 mm. (0.2 per cent) error. Hence, the grid is quite sensitive to deviations from expected values. We would predict a "good fit" from the graph. Computations for the more exacting chi-square test for goodness of fit are given in table 1. The computed χ^2 for each sample lies between the limits for two values of p as given in the table, and as read from detailed tables for values of the probability integral of χ^2 in Pearson and Hartley.[23] To interpret p, employ the rule given by Fisher,[24] namely, if p is between 0.1 and 0.9 there is certainly no reason to suspect the hypothesis tested. In table 1, values of p are of such magnitude that we have no reason to suspect the hypothesis that for each of these three muscular actions, the ratio force/body weight is distributed in the universe as a Gaussian or normal probability function. We may proceed on this assumption to apply the statistics from our samples in devising reference norms.

Transformation. For the muscular actions under consideration we have three numerical values of x, the ratio force/body weight which we shall now abbreviate f/w. The normal reference in terms of f/w units are 0.62 for hip extension, 0.98 for knee extension, and 2.42 for ankle plantar flexion. Their associated standard deviations are 0.089, 0.124, and 0.330 respectively. It is difficult to make comparisons readily with such figures. A percentage scale, which represents average normal as 100, with relative variance adjusted accordingly, is much easier to interpret both directly and for comparative purposes. We have a large number of muscle systems to evaluate. Whenever possible it will be especially helpful to represent each system on a percentage scale, and seek the simplest computational procedures for the transformation. For the three systems we are considering, this can be done by a legitimate and simple method. The transformation factors Tx given in table 1 are the multipliers required to obtain the product 100.00, when the corresponding x is used as the multiplicand. Similarly, the *S*'s, when multiplied by the appropriate Tx, become the correct value for the standard deviation of the distribution as projected on the percentage scale, instead of on the scale using f/w units. For convenience, we shall refer to this transformed scale as the %N scale. The *S* values on the %N scale become 14.41, 12.42 and 13.67 for the three actions. As a practical compromise, we may regard the *S* as 15 per cent for each action without serious error in interpretation.

To evaluate an individual's rating on the %N scale, let us use an example with approximate multipliers. We measure hip extensor force in the prescribed manner on a patient and obtain a value of 40 pounds. His body weight is 160 pounds. The ratio $f/w = 40/160 = 0.25$. To transform, we multiply by $Tx = 162$ and obtain the product 41 (rounded). This means that the patient's hip extensor force is 41 per cent of average normal expectation. The same procedure is used for the other two actions, except we use $Tx = 102$ for knee extension and $Tx = 42$ for ankle plantar flexion.

This procedure, justified by the statistical analysis, is applicable to any individual, male or female, between the ages five and 29 years. We have derived, then, three powerful norms and reduced them to comparable scale units for three muscular actions. The standard scale units may be represented for simplicity by the symbols Txf/w, which is the computational ratio for obtaining the %N rating.

It is important to observe that individuals included in the range of the Gaussian curve of best fit to the data are *not* to be regarded as equally "normal" in the functional sense. The reference norm ($x = 100$) permits evaluating the ex-

ceptionally strong, as well as exceptionally weak, individuals within the Gaussian distribution. Thus, the person who attains a rating of 130 %N is decidedly superior in strength, whereas one with a rating of 70 %N has about half as much effective strength. Both persons would be included within the Gaussian curve at approximately an $x \pm 2S$ (or $4S$ total) distance apart. Instead of referring to "normal" as an absolute value or concept, we are obliged to think of "normal" relative to average expectation, and rate an individual accordingly. No individual would be called precisely normal. The reference is relative to x. A good example of a clinical application is a patient who demonstrated 125 %N on the right and 78 %N on the left for knee extension. In the general population normal (negative history) samples, differences between right and left seldom exceed 12 per cent on the %N scale. In the case of this patient, we can conclude that there is unequivocal evidence of bilateral asymmetry, with marked weakness on the left relative to the right, even though both values remain within the Gaussian curve at a distance less than $x \pm 2S$ apart. The patient was fully aware from personal experience that a unilateral defect exists, even though he was told upon good authority that he is "normal" on both sides.

Application of Standardized Norms to Evaluation of Paresis

The purpose in this final section of the paper is to show how effectively the standardized norms developed for the actions hip extension, knee extension, and ankle plantar flexion can be applied to estimating the level of paresis among postpoliomyelitis patients quite independently of any other considerations. However, since the studies intentionally provided actual clinical or manual grade evaluations on the same patients that were measured by the quantitative electronic myodynagraph methods, we shall also consider how the manual grade categories fail to differentiate levels of paresis in relation to the quantitative %N scale as discussed in the preceding section. Because the operational information is so involved, a full report on all phases of these studies and methods used can not be included here. Sufficient detail to facilitate interpretation of the data (tables 2-4) and the charts (figs. 5 and 6) will be provided. Again, the reader is referred to three forthcoming papers for the background knowledge.[19-21]

Over the period from 1948 through 1953 a series of studies was pursued in several hospitals, rehabilitation centers, and special clinics to develop the necessary standardization of methods for testing patients and to acquire a large volume of measurements on postpoliomyelitis patients for the purpose of determining the actual degrees of weakness presented, to evaluate "error" of manual muscle testing methods, and to demonstrate clinical applications of quantitative methods. The tests included some 37 actions of the principal joint motions of the upper and lower extremities. In these earlier studies, tests on the trunk and finger motions were not included. Altogether, about 1,200 postpoliomyelitis patients were tested, but some 300 did not complete the full rounds for 37 actions. Proper evaluation of this information can be made only after useful and directly applicable reference norms have been derived. Otherwise, a multitude of measurements representing paresis of varying levels and patterns between different muscle systems of individuals are on hand, but there is no basis for evaluating them against an acceptable normal standard.

Adequate data and appropriate statistical treatment were not available until recently to carry forward the original plan to evaluate the patient data against an acceptable normal reference. Measurements on patients who were graded "normal" clinically could not be used as a reference norm because (as we shall see) most of them had in fact significant amounts of paresis that were not detected by clinical examination. I was aware of this trend in 1949 from sampled comparisons of normal public school children of the same age range. Besides, one could not validly define a reference normal group as patients with a history of acute poliomyelitis, who were regarded as

Table 2: Statistics from Distributions of the Ratio Force/Body Weight Postpoliomyelitis Patients by Manual Grade Class (DWW)* with Transformation to Per Cent of Normal Reference Muscular Action : Hip Extension

Group	Hips	Ratio Force/Body Weight x	Ratio Force/Body Weight S	Transformed Values % Normal x	Transformed Values % Normal S	Relative Variance RV%
Reference Normal Boys, girls, men and women (5-29 years)	3,220	0.6192	0.0892	100.00	14.41	14.41
Postpoliomyelitis patients by manual grade class (DWW)*						
Normal, both sides (NN)	664	0.404	0.111	65.25	17.93	27.48
Good (G)	287	0.264	0.093	42.64	15.02	35.23
Fair-plus (F+)	102	0.171	0.080	27.62	12.92	46.78
Fair (F)	116	0.124	0.066	20.03	10.66	53.23
Fair-minus (F—)	47	0.044	0.020	7.11	3.23	45.45
Poor-plus (P+)	68	0.030	0.013	4.85	2.10	43.33
Poor (P)	59	0.033	0.013	5.33	2.10	39.39
Poor-minus (P—)	33	0.019	0.008	3.07	1.29	42.11
Trace (T)	88	0.012	0.008	1.94	1.29	66.67
Zero (Z)	12	0.008	0.006	1.29	0.97	75.00

*(DWW): As defined in Daniels, Williams & Worthingham.[25]
Transformed value = ratio statistic × 161.499

RV% value is a good index to the discriminating effectiveness of the classification: the smaller the value of RV%, the more definitive is the classification. Adjacent classes with a large value for RV% are not clearly differentiated.

Table 3: Statistics from Distributions of the Ratio Force/Body Weight Postpoliomyelitis Patients by Manual Grade Class (DWW)* with Transformation to Per Cent of Normal Reference Muscular Action : Knee Extension

Group	Knees	Ratio Force/Body Weight x	Ratio Force/Body Weight S	Transformed Values % Normal x	Transformed Values % Normal S	Relative Variance RV%
Reference Normal Boys, girls, men and women (5-29 years)	2,728	0.9792	0.1242	100.00	12.68	12.68
Postpoliomyelitis patients by manual grade class (DWW)*						
Normal, both sides (NN)	752	0.524	0.152	53.51	15.52	29.01
Good (G)	333	0.416	0.083	42.48	8.48	19.95
Fair-plus (F+)	244	0.191	0.057	19.51	5.82	29.84
Fair (F)	192	0.089	0.034	9.09	3.47	38.20
Fair-minus (F—)	69	0.062	0.025	6.33	2.55	40.32
Poor-plus (P+)	108	0.039	0.017	3.98	1.74	43.59
Poor (P)	135	0.025	0.016	2.55	1.63	64.00
Poor-minus (P—)	123	0.019	0.014	1.94	1.43	73.68
Trace (T)	183	0.010	0.008	1.02	0.82	80.00
Zero (Z)	159	0.007	0.006	0.71	0.61	85.71

*(DWW): As defined in Daniels, Williams & Worthingham.[25]
Transformed value = ratio statistic × 102.125

RV% value is a good index to the discriminating effectiveness of the classification: the smaller the value of RV%, the more definitive is the classification. Adjacent classes with a large value for RV% are not clearly differentiated.

Table 4: Statistics from Distributions of the Ratio Force/Body Weight Postpoliomyelitis Patients by Clinical Grade Class (DWW) & (EKI)* with Transformation to Per Cent of Normal Reference Muscular Action : Ankle Plantar Flexion

Group		Ankles	Ratio Force/Body Weight $\bar{x}$	Ratio Force/Body Weight S	Transformed Values % Normal $\bar{x}$	Transformed Values % Normal S	Relative Variance RV%
Reference Normal Children, adolescents, and adults, M & F (5-29 years) ...		4,718	2.4107	0.3295	100.00	13.67	13.67
Postpoliomyelitis patients by clinical grade class (DWW)	(EKI)						
Normal (NN)	5-5	1,236	1.960	0.496	81.31	20.58	25.31
Good (G)	4	312	1.115	0.188	46.25	7.80	16.86
Fair (F)	3	329	0.823	0.176	34.14	7.30	21.39
Fair-minus (F—)	2+	214	0.533	0.174	22.11	7.22	32.65
Poor (P)	2	128	0.316	0.153	13.11	6.35	48.42
Poor-minus (P—)	1+	84	0.182	0.101	7.55	4.19	55.49
Trace (T)	1	29	0.069	0.054	2.86	2.24	78.26

*(EKI): Grading scale employed at Elizabeth Kenny Institute, Minneapolis (cf. Beasley[7]).
Equivalent ratings between DWW and EKI scales are listed, but all of these patients were graded and tested at EKI.
Transformed value = ratio statistic × 41.482

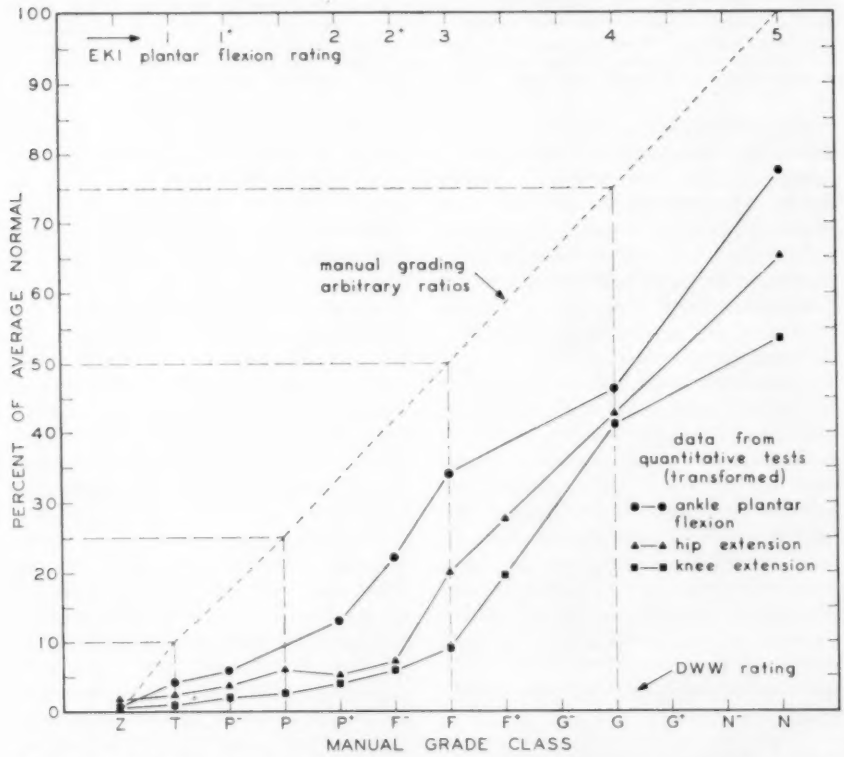

Fig. 5 — Relationship between manual grade classifications of muscular strength among postpoliomyelitis patients and quantified ratings based upon measurements of muscular force on normal subjects and on the same patients. The graph combines results of analyses given in tables 1 to 4, inclusive. The DWW rating refers to definitions of classes as given by Daniels, Williams and Worthingham.[25] The EKI rating refers to definitions of classes employed at the Elizabeth Kenny Institute for ankle plantar flexion only (cf. Beasley[7]). Departure of the data plots from the diagonal hyphenated line indicates the "error" of manual grading evaluations when the indicated arbitrary percentages are employed as equivalent to the letter or number grades. The graph also shows the average percentage level for each manual grade classification of muscular strength relative to the average reference normal (table 1).

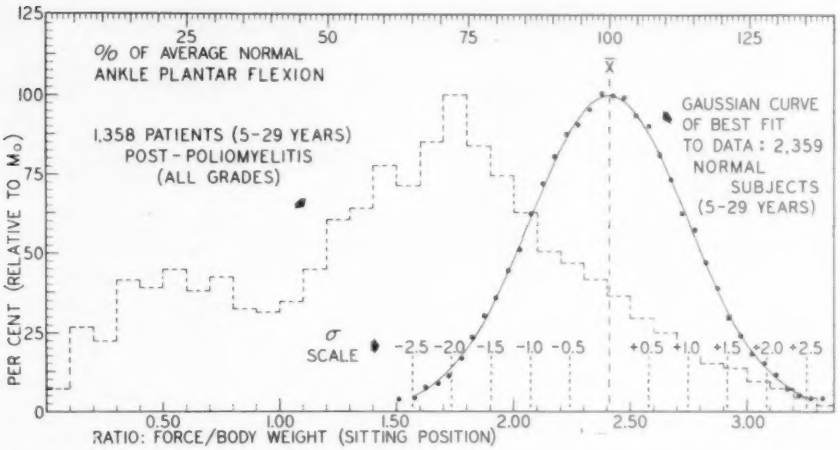

Fig. 6 — The graph shows the effect of poliomyelitis on a large sample of patients in reducing ankle plantar flexion strength. The histogram (broken lines) is not strictly a bimodal distribution; that is, we do not find "paralytic" and "non-paralytic" effects, but rather a continuum in the degrees of departure from normality. There is, however, a suggestion of two main effects: moderate and severe degrees of paresis. But the overlap is so extensive that bimodality is not a correct interpretation. The symbol M_o on the ordinate legend means modal class, which was set at 100 for each of the two samples that are compared.

"normal clinically" upon discharge or at subsequent examination. That would be fallacious logic, i.e., *petitio principii!* An essential part of the problem is to evaluate "clinical normal" against an independent, valid criterion derived from measurements on population groups with a negative history relative to those forms of disease and trauma that would bias the estimates of normal muscular strength. The patients, moreover, included wide age ranges, both sexes, and varieties of body build (height, weight, etc.). In evaluating such a heterogeneous sample, with the added variable of complex patterns and degrees of paresis among individuals, it is essential that standard norms somehow tie age, sex and body build together with a common denominator, so that larger groups of patients can be assembled for evaluation relative to a unified norm. Now this can be done for the three actions under consideration.

Manual Grading Scales

The studies, from which the statistics (tables 2 and 3) were derived for hip extension and knee extension, were all carried out in locations where the manual grading system described by Daniels, Williams and Worthingham[25] was in continuous use. All of the physical therapists who conducted the manual examination evaluations were highly competent and with many years of professional clinical experience. Their use of the manual method, therefore, may be regarded as representative of the most accurate results that are realized in practice.

In the United States, and in some foreign countries as well, this system is well known. For the benefit of those not so familiar with it, definitions for manual grade classes and letter grade designations as used in tables 2 and 3 are given here for ease of reference. Corresponding percentage ratings that are used in the manual system for interpretation are listed also. The clinical rating scale for ankle plantar flexion is discussed in relation to table 4, since considerations for that action are different.

The tables show ratings also for steps that are intermediate between these main divisions. Some examiners claim they can consistently grade at these intermediate points. The partial step categories for Good-minus, Good-plus and Normal-minus were not included in the tables because such grades as they appeared in the records were too few in number, in the first place, and they were not at all

Grade	Letter	%	Definition
Normal	N	100	Complete range of motion against gravity with full resistance.
Good	G	75	Complete range of motion against gravity with some resistance.
Fair	F	50	Complete range of motion against gravity.
Poor	P	25	Complete range of motion with gravity eliminated.
Trace	T	10	Evidence of slight contraction. No joint motion.
Zero	Z	0	No evidence of contractility.

differentiated from the major letter category with which they were associated. A critical analysis of this system of grading, with examples of how it actually works out in practice, is given in the more detailed papers.[19-21]

Application to Hip Extension

Methods of Testing. The procedure used in testing this action on patients, both for the quantitative electronic myodynagraph tests and the manual grading, was comparable to that used in the tests on normal subjects as described previously. Two positions were used: prone and supine lying. In either case, measurements were made with the tested hip in 45 degree flexion, and the contralateral one counterpoised at full extension. In the prone position, both legs projected beyond the end of the table. The non-tested leg was supported on an extension rack level with the table surface. For a grade of Fair or better, using this positioning, the tested leg was lowered toward the floor and the patient was required to extend the hip through range of motion, with the knee straight, to a position even with the contralateral leg. Patients who could not perform in this manner were given the manual tests sidelying, but the electronic myodynagraph tests for these used the supine lying position as illustrated (fig. 3).

Measurements and Ratios. Only patients in the age range five to 29 years are included in this analysis. For this reason, the statistical estimates are directly comparable with the normal (negative history) groups (table 1). Three measurements each, for right and left, were recorded, and the average values for each set of three was used as the measure of strength. The ratio of this average to body weight of the patient was computed. These values were classified according to the manual grade given by the physical therapist as an independent evaluation. Statistics were then computed for these distributions. The average (x) and standard deviation (S) for these distributions are given in table 2. These x and S values were multiplied by the appropriate transformation factor ($Tx = 161.499$, table 1) and the products are listed. These values are to be read as percentage relative to average normal on the %N scale as described previously. For convenience of comparison, the reference statistics for the normal (negative history) group are given on the first line of the table.

The transformed values give us a quantitative estimate of the amount of paresis, or deviation (by subtraction) from expected average normal on a linear %N scale. We know now, for the first time, the actual levels of paresis; relative to a valid norm, that are present when the various manual grade evaluations are assigned. We can estimate also the magnitude of error relative to the assumed "percentage" values. The lack of meaningful differentiation is shown by the magnitude of the transformed S values considered in relation to adjacent x's.

Trends. With the full explanation already given on how to interpret the final evaluations in table 2, the reader can easily interpret the full significance of the trends shown. The group listed as "Normal, both sides (NN)" comprises 332 patients for whom the manual grade "normal" in hip extension was given for both right and left. The other manual grade groups from Good on down to Zero comprise 406 other patients for whom neither side was graded normal; that is, grades less than normal were given for both sides. Excluded from this particular table is another group of patients who were graded normal on one side only.

Of particular significance is the evaluation shown for the "Normal, both sides" group. Here 332 patients, classified as normal both sides, show an x value only 65 %N on the standard scale,

with a transformed S of 18. This means in general that extensive and significant paresis exists among the postpoliomyelitis patients who are discharged clinically as "normal." The Fair group, ordinarily rated at 50 %N, actually have an x value of only 20 %N on the standard scale. Note especially also the overlap between adjacent groups, by comparing $x \pm S$ ranges. There is very poor differentiation between categories. The relative variance percentage trends given in the last column may be used to estimate relative error between categories. It is computed from the relation $100\ S/x$, and shows the percentage of S relative to x.

Application to Knee Extension

Method of Testing. Two positions were used for all of the tests on patients included in this analysis. All who could perform in the gravity opposing position were tested semi-supine lying. Both legs were over the end of the table with a firm, rounded support under the thigh near the knee joint. A broad, padded strap served to hold down the pelvis for those who required it. The shoulders and head were supported sufficiently high to produce a position of trunk flexion in moderate degree. This positioning reduces stresses in the lumbar area during maximum effort trials. Those who could not extend the knee against gravity through range were positioned prone lying with gravity assisting. A padded strap over the thigh posteriorly and near the knee joint provided necessary counterpoise to the leg being tested. In both positions, force was measured with the knee at 45 degree flexion at a point near the ankle, as for hip extension. Manual evaluation grading followed the instructions of Daniels, Williams, and Worthingham[25] for this action.

Measurements and Ratios. Three measurements were recorded for each side. The average value for each set of three was used to represent the strength (per side) for knee extension. Corrections were made for the gravitational component force (additive or subtractive) for the gravity opposing and gravity assisting positions, so that net force was used in the final analysis. Ratios of force to body weight were computed and treated in the same manner as the data for hip extension, as described previously. The average (x) and standard deviation (S) of these distributions are given in table 3, classified according to the manual grades assigned for each knee singly. These two statistics were multiplied by the proper transformation factor ($Tx = 102.125$, table 1) to obtain ratings on the %N scale. These products are listed also in table 3.

Trends. For convenience of comparison, reference norm statistics (from table 1) for the 1,364 normal subjects (negative history) are repeated on the first line of data in table 3. Trends shown by the statistics for patients should now be interpreted readily. In the sample there are 376 patients who received the manual grade evaluation of "Normal, both sides (NN)." There are 773 additional patients who were graded less than normal on either side. These are classified by individual knees, of course, in accordance with the assigned manual grades. Excluded from this table is another group of patients who were graded normal on one side only.

There are many interesting trends shown in the table for the patients, as the reader may discover through exploration. The "Normal, both sides" group has an expected average value (x) for force/body weight of only 0.524 in comparison with the ratio 0.979 for the standard normal group. On the %N scale, this ratio for the "Normal, both sides" patients becomes 53 %N. This means what it says, namely, that 376 patients who were classified clinically as normal for both right and left knee extensors, actually are on the average only 53 per cent of normal in comparison with the standard normal reference. The hip extension rating for "Normal, both sides" patients was 65 %N. This difference may suggest that there was much greater damage to knee extensor neuromuscular systems from poliomyelitis attack than there was to the hip extensor systems. Other contributing factors must be considered, however, such as whether the manual tests leading to "Normal,

both sides" grades are equally accurate for these two actions. As will be shown elsewhere, they are not.[19-21] The %N scales themselves, however, are directly comparable from the way in which they were derived. The Good group, ordinarily rated at 75 %N in the manual system, has an x value of only 43 %N on the standardized scale. The Fair group, ordinarily rated at 50 %N in the manual system, receives a rating of only 9 %N relative to the quantitative, standardized norm. The Poor group, ordinarily rated at 25 %N in the manual system, actually has an x of only 2.6 %N on the standardized scale. There is pronounced discrepancy between arbitrary and quantitative ratings. An instructive exercise for the reader is to study the overlap between adjacent classes, using a little arithmetic, by computing $x \pm S$ values for each class in the %N columns. In doing this, one may confirm the observation that there is very poor differentiation between graded classes below Fair, where manual muscle testing is said to be most "accurate."

Application to Ankle Plantar Flexion

Clinical Grade Definitions. All of the data presented here for the ankle plantar flexion action was accumulated during a concentrated period of testing at the Elizabeth Kenny Institute, Minneapolis, mainly during 1958 and 1959. The grading scale used by the medical staff at this institution differs from the definitions of Daniels, Williams and Worthingham in some respects, although for results obtained in practice as well as in general concept, there are equivalent categories. The definitions for the Elizabeth Kenny Institute grades are given here. Numbers only are used, and these are not translated into nor presumed to have "percentage" values. The letter and name grades, as well as the percentages, placed beside the Elizabeth Kenny Institute grades are my own estimates of the equivalent classification in the Daniels, Williams and Worthingham grading. The equivalence in meaning is so close, however, that there appears to be little room for a difference of opinion. For further discussion of this problem, refer to two other publications.[7, 21] All grades for three and above are weight-bearing. Grades below three employ prone or supine positions on a table. Differentiation between gastrocnemius and soleus is made only for the non-weight-bearing grades below three. Here the usual knee extended versus knee flexed assumptions are applied relative to isolating soleus action, and the definitions given below are applied, presumably, to grading of soleus in the knee flexed position.

Daniels, Williams & Worthingham Grade	%	Elizabeth Kenny Institute Grade	Elizabeth Kenny Institute Definition
Normal	100	5	Raises body-weight with ease well into the arc of motion. Maintains stable rise. Number of times not used; once is enough if done well.
Good	75	4	Raises heel off floor considerably but with difficulty: not with ease as in grade 5.
Fair	50	3	Holds body-weight with heel slightly off floor, or can hold body-weight off floor without being able to raise body-weight from neutral standing position. May require considerable help from examiner.
Fair-minus	?	2+	Sustains heavy manual resistance, but can not hold body-weight against gravity in any manner.
Poor (+?)	25	2	Can move foot through full range of motion in which there is no limitation imposed by contracture, and may offer up to moderate resistance to manually applied force.
Poor-minus	?	1+	Some motion of the calcaneous, and more definite tension in tendon than for grade 1.
Trace	10	1	Only a trace of motion or tension observed in Achilles' tendon, but no motion of calcaneous.
Zero	0	0	No evidence of motion or tension in Achilles' tendon.

Method of Testing. In the long-term experience of this program since 1945, more attention has been given to effective ways for measuring the powerful forces of the ankle plantar flexion system than for any other action. Seven different methods were explored thoroughly. It is my opinion that we have not yet been able to effectively measure the full force for this action with the knee fully extended, because every method tried required reactive support by the hip,

back and shoulders. These latter musculoskeletal systems impose limitations that prevent the full force of the ankle plantar flexion system to be applied. The method finally adopted here for standardized procedure, although performed in the sitting position with the knee flexed 90 degrees, has up to now proved to be the most satisfactory of all. In fact, from comparative studies, I have reached the conclusion that flexing the knee 90 degrees, *and* with the ankle at the 90 degree neutral position, does not reduce the ankle plantar flexion thrust force at all, as compared with that produced when the knee is straight *and* the heel has been raised from neutral standing to about one-half the range of vertical rise. The standard method adopted is reliable and produces very little stress on muscle systems not directly involved in the ankle plantar flexion action itself. To measure validly the residual ankle plantar flexion forces at levels below about 10 pounds, referred to the metatarsal heads for the application of leverage, it is necessary to use an alternative method, which requires application of the load with my manual force gage, as described elsewhere.[1]

The essential requirements of the standard position are the following. The subject is seated on a firm platform, adjustable in height so that 90 degree flexion of the hip and knee joints can be assumed by different subjects. Both feet rest at the same level on another platform that clears the floor by 12 inches to allow room for anchoring the axial tensiometer gages below a lateral slit in the footrest platform. A padded semicircular plate of 16-gage stainless steel is placed distally on the thigh over the knee-joint. This serves the dual purpose of providing a coupling to the axial tensiometer gages and distributes the axial load of the high-level thrust force over a wide area of the thigh, thereby increasing the applied pressure area and reducing the psi of the load. A double-length roller chain passes over this plate in two directions and is coupled at a fixed length by a suitable fastener on top of the plate. At the other end, the roller chain passes through the platform slit and thence around a sprocket wheel that is coupled with rotary freedom to the axial tensiometer gages. This rotary freedom is necessary, since it permits the two lengths of the roller chain to automatically equalize. The axis of the axial tensiometer gage is lined up vertically with the axis of the tibia. The starting position of the test is with the ankle joint in about 10 degree dorsi-flexion. The length of the roller chain is adjusted so that, when the thrust force is developed, the heel rises sufficiently to bring the ankle joint to the 90 degree neutral position.

Measurements and Ratios. For each patient in the age range five to 29 years included in this analysis, two maximum effort trials of 10-seconds' duration were recorded for right and left. The average value of these two trials for each side separately was employed in computing the force/body weight ratios. These ratios were classified according to the Elizabeth Kenny Institute clinical grade assigned. The statistics, x and S, for these distributions are given in table 4. These ratio values were multiplied by the appropriate transformation factor ($Tx = 41.482$, table 1) to obtain the equivalent values on the %N scale. These also are listed in table 4.

Trends. The statistics for the 2,359 subjects five to 29 years of age in the ankle plantar flexion reference normal group are given on the first line of table 4. The expected average value (x) for the ratio force/body weight (f/w) is 2.41 and the standard deviation (S) is 0.330 (rounded). Consider what this means in terms of the Gaussian curve and expected forces. Our statistical analysis showed that we are justified in assuming that the ratio f/w is normally distributed in the universe, and that if we continue indefinitely to draw samples of size N_d (2,359 subjects) through the age range five to 29 years, for 99 per cent of such samples the x of f/w will fall within the limits of 2.42 and 2.40. For a subject whose body weight is 175 pounds, x is 422 pounds. The $x \pm 2.5S$ range is from 278 to 567 pounds. For a 50 pound child, say at six years of age, x is

121 pounds. The $x \pm 2.5S$ range is from 80 to 162 pounds. x is 100 %N. The range for $x \pm 2.5S$ on the %N scale is 100 ± 34, or from 66 %N to 134 %N. These values are at the extreme tails of the Gaussian curve. Obviously, subjects included within this range are not equally "normal" in the functional sense. At 66 %N subjects are definitely weak. At the 134 %N level, subjects are exceptionally strong, active, vigorous. What is normal? The reference is $x =$ 100 %N, the average or expected value, accompanied functionally by average or expected strength and performance. Similar reasoning applies to the reference norm statistics as given for the hip and knee extension actions.

The computations for postpoliomyelitis patients as listed in table 4 are for 618 patients graded 5-5, that is, grade 5 was assigned to both right and left sides. There are in addition 548 patients who were graded less than 5 on both sides. Excluded from this table are two other groups: those graded 5 on one side only, and those graded zero on one or both sides. The x of f/w for the 5-5 group is 1.96, which has the value 81 %N on the normal reference scale. The histogram for this group, as studied separately, shows marked positive skewness.[7] The mode is at approximately 1.70 for f/w, which is at 71 %N. The lower limit of this histogram is at almost precisely 1.00 for f/w, which is 41 %N. The upper limit is at 3.30 for f/w, which is 137 %N. The criterion for exclusion-inclusion in this group, as given above, is the ability to rise on tiptoe, well into the arc with ease and without any help from the examiner. This criterion in practice is fulfilled, but it does not discriminate between patients who actually range from 41 %N to 137 %N. Paresis resulting from poliomyelitis among these patients, however, is very definitely present through the range from 41 %N to 70 %N. Because of the marked positive skewness of the histogram, with the mode at 71 %N and x at 81 %N, we may conclude also that the population of 5-5 patients exhibited further evidence of moderate paresis in the range from 70 %N to 85 %N or above, because of the exaggerated proportion of cases in this range.

The statistics for the other clinical grade classes show successively lower levels of force and %N ratings, as judged by the x values. However, there is very poor differentiation between adjacent groups, as indicated by the $x \pm S$ ranges. The overlap is so broad that these classes could not be used in any important study where the grading of paresis must be done with meaningful accuracy. The same conclusion applies to the analysis as given for hip and knee extension. In table 4 the statistics for the grade 3 are especially significant, because this grade involves a fairly objective criterion, namely, "holds body-weight with heel slightly off floor without being able to raise body-weight from neutral standing position." The x of f/w for this group is 0.82, which indicates a force level below the body weight of the patients, hence, not enough force available to raise the body-weight. This level is 34 %N. The x of f/w is 2.41 for the normal reference group. Body-weight represents 100/2.41, 41 per cent. When the available force approaches a ratio 1.00 f/w = (41 %N), the patient can just barely pass the tiptoe rise test for grade 5. The grade 4, in between, almost completely overlaps with grade 3 on one side and with grade 5 on the other, as would be expected from the inherent relationships already considered. For grade 4, the examiner must judge "relative ease" with which the test is performed. This is, of course, a variable and subjective criterion.

Application to Epidemiologic Surveys

There are many examples in the literature, even in recent years, where the arbitrary percentage values as assigned to the manual grade categories are utilized directly in clinical research studies, as if these values truly represent degrees of paresis on a quantitative scale. Similarly, in the exceedingly important epidemiologic surveys, such as the evaluation of Red Cross gamma globulin[26] and of the Salk vaccine,[27] numerical values on the same linear base as the per-

centage scale were employed in a manner that assumed mathematical validity of the scale divisions. Eventually, it will be worthwhile to estimate the real error that entered into those evaluations, as a permanent scientific contribution. This can not be done until satisfactory normalized scaling has been completed for many other muscle groups. We can not generalize to all muscular actions from the three actions considered in this paper. There are definite points available, however, from the trends shown in tables 1 to 4 that indicate gross errors in evaluating amounts of paresis entered into the survey methodology by assuming invalid numeric values for the manual muscle test scores. These points have been brought out in the preceding discussion.

The basic statistical trends represented by x values for all classes of subjects and clinical grades included in tables 1 to 4 are consolidated into one graph (fig. 5) for convenience of comparison and visualization of trends. This graph shows the basic relationship between the x values obtained in the quantitative measurements of muscular forces, when these were classified according to the manual grade assigned for the muscle system. The meanings of the Daniels, Williams and Worthingham and the Elizabeth Kenny Institute grades as represented on the chart have been explained previously in this paper. In the chart, the vertical ordinate scale has two meanings: first, it represents an arbitrary "percentage" scale to which the manual grade classes are referred in accordance with customary values assigned; secondly, it is a quantitative percentage scale used for plotting the actual x values as transformed to %N scales, in accordance with the computations given in tables 2 to 4. The hyphenated line that runs diagonally across the graph locates the points where the manual grade classes are presumed to be customarily. The plotted data points indicate where they actually are from the present analysis. The discrepancies between the two sets give a quantitative estimate of error in the manual grade percentages — error in the sense of difference between assumed and obtained values.

With the adequate explanations that have been given, detailed interpretation of the graph is left to the reader. Clearly enough, there is much significant paresis among groups of postpoliomyelitis patients classified as normal clinically for all three of the actions studied. Secondly, the amount of error in the various manual grade classes differs for each of these three actions. Another definite trend for these three actions is that throughout all manual grade classes, the quantified %N rating is grossly less than the ratings assigned arbitrarily. In the interpretation of the survey data, therefore, one may conclude that the amount and incidence of paresis was greatly in excess of the amount actually estimated by the scoring procedure that was used.

A widespread view that appears in the literature currently postulates the effects from poliomyelitis as being divisible into two categories: paralytic and non-paralytic. If this were a valid concept, then quantitative muscle tests on a large population of postpoliomyelitis patients should result in two separate distributions: one at a "paralytic" level far down the line from "normal"; the other, if truly non-paralytic, should remain essentially within the bounds of a distribution for measurements on a large sample of normal subjects without a history of acute poliomyelitis. No such demonstration has ever been produced thus far. From the present study we can produce a comparison of this nature for three actions: hip and knee extension, and ankle plantar flexion. We have included here one such graph for the action ankle plantar flexion (fig. 6).

The graph may be interpreted, from our probability analysis, as showing the effect of poliomyelitis on a large sample of people (1,358) in the age range five to 29 years. The analysis relative to table 1 justifies the assumption that the measurements on these patients, before they had poliomyelitis, fell within the borders of the Gaussian curve for the measurements on the 2,359 normal subjects with a negative history *re* poliomyelitis and other neuromuscular diseases. The histogram (broken lines) represents, therefore, the effects from

poliomyelitis attack. The form of this histogram is not at all compatible with expectation, if poliomyelitis is assumed to produce "paralytic" or "non-paralytic" effects in a population. Rather, there is a continuum in degrees of paresis, with moderate amounts being more frequent than truly severe amounts. The relative frequency of different amounts of paresis can be read easily on the standardized %N scale along the upper border of the chart.

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Evaluation and Treatment of Low Back Pain Due to Mechanical Causes

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● Injury to the low back may be due either to a sudden extreme force which exceeds the compressive strength of bone or the tensile strength of ligaments and connective tissue, or to a prolonged stress which stretches ligaments and connective tissue and causes pain. In normal daily activity high tensile stresses are exerted against the ligaments and connective tissues in the low back. During periods of quiescence the muscles relax and support for the vertebral column is provided by the ligaments. Prolonged stress on these ligaments causes strain and pain. Under abnormal conditions of metabolic imbalance or inflammation the strength of bone and connective tissue is diminished and injury may occur as a result of mild stress. Improper or inadequate support during bending, sitting or reclining may produce prolonged stresses which will injure these supporting tissues. Proper support during sitting is especially important. Evaluation of the patient with an injury to the low back must be thorough to establish whether there is injury to bone or joints, or compression of nerve roots. In all cases there is injury to connective tissues. The site of injury should be localized as definitely as possible by physical examination, functional tests and roentgenologic studies. Electromyography is useful to establish involvement of motor nerve roots. Adequate therapy includes support and rest so that healing can occur, relief of pain, removal of the products of inflammation, restoration of normal mobility and re-establishment of normal strength. Patients must be instructed in proper posture, precautions against back strains during daily activity, and exercises to maintain the mobility, strength, and endurance in the muscles of the back.

Low back pain either occasional or chronic is an almost universal disability among adults. Although a careful history will usually elicit some traumatic incident in the past associated with the subsequent onset of backache, there are many persons for whom this trauma was rather mild and may have occurred long ago. There may be a history of an insidious onset of back pain without unusual trauma, associated with the story that the pain was aggravated by prolonged standing or prolonged sitting, or even that the pain developed during the night while the patient was lying in bed. Normal activities at home, at work, or at play are such as to expose the low back to relatively high degrees of stress at frequent intervals. Consequently, the incidence of low back strain and backache is high.

It is obvious that backache is a symptom which may arise from many causes. Pain may be referred to the back from visceral lesions or projected to the back from a neural origin. The patient must, therefore, be given a thorough evaluation to determine the cause of his backache and to avoid the pitfalls which may occur when treatment is purely symptomatic. However, in order to limit this paper to a reasonable length the discussion will be confined to pain arising from damage to the structures in the back.

The low back is an extremely complex structure and pain may arise from any area. Therefore, the conditions which may cause low back pain must be considered in evaluating the problem prior to prescribing a rational treatment. The low back must be considered as a mobile structure rather than as a static column. During normal activities the vertebral column is frequently moved through its full range of motion. Such activity puts compression and shearing stresses on the bony components of the back and tensile stresses on the ligamentous and muscular components. Damage to any of these parts may give rise to pain.

The lumbar spine is comparable to a jointed column which can be maintained erect only because guy-lines maintain one vertebra above another (fig. 1). The five lumbar vertebrae are separated

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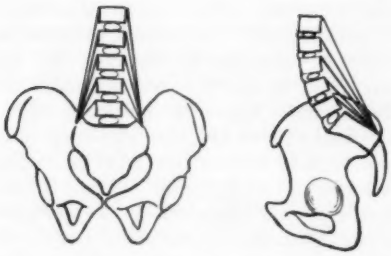

Fig. 1 — The lumbar spine *(left)* is a jointed column which is maintained in an erect position only because of the external support provided by guy-lines. The intervertebral discs provide hydraulic joints which are resistant to wear from motion under high compression. The lumbar spine *(right)*, mounted on the slanting sacrum, is always eccentric in position and always requires some external support for balance.

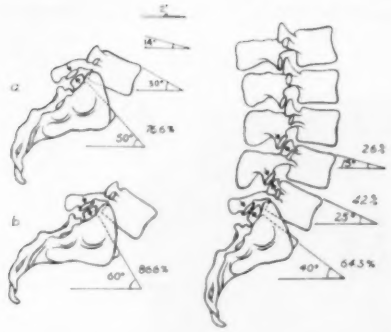

Fig. 2 — The shearing stress on the intervertebral ligaments and apophyseal joints of the lumbosacral junction and the lumbar spine is proportional to the angle of the surface of the vertebra with the horizontal. At the normal sacral angle of approximately 40 degrees the shearing force on the apophyses and ligaments is 65 per cent of the superincumbent weight. This shearing force increases if the anterior tilt of the pelvis is increased and diminishes when the back is flattened.

by flexible intervertebral discs which permit movement between the vertebrae. The intervertebral disc — composed of a dense capsule, the annulus fibrosus, surrounding the gelatinous mass of the nucleus pulposus — provides a mobile hydraulic junction between vertebrae which allows motion under extremely heavy pressure and is resistant to wear. However, eccentric loading of any type would cause toppling of this column if it were not for restrictive ligaments or contracting muscles. This vertebral column is seated on the inclined plane of the superior surface of the sacrum at an angle of approximately 45 degrees. Therefore this column always is eccentrically loaded and requires external support.

Such a jointed column supported by guy-wires is least resistant to shearing forces perpendicular to the long axis of the column. Longitudinally placed ligaments or muscles provide little support against such shearing forces. In the spinal column this shearing force is very large (fig. 2). If the sacral angle, the angle between the superior surface of the sacrum and the horizontal, is 50 degrees, the shearing force in the plane of the superior surface of the sacrum is equal to three-fourths of the superincumbent weight imposed upon the column. If the sacral angle is 40 degrees, the shearing stress is approximately 65 per cent, and if the sacral angle is 30 degrees, the shearing force is 50 per cent of the superincumbent weight. The two apophyseal joints between the adjacent vertebrae provide rigid resistance to this shearing force at the same time that mobility is preserved. Since the center of motion of the vertebrae is anterior to the apophyseal joints these joints have a sliding action whenever the spine is moved. These sliding motions may produce traction and tearing of the capsules of the apophyseal joints.

Restriction of the motion of the vertebral column other than longitudinal compression or posteroanterior shear is provided by connective tissue or muscular elements. The muscles by their nature of contractility and distensibility can provide variable support within a wide range of motion. The muscles provide intermittent forces to balance the vertebral column at rest or to support it during activity. For the economy of energy or because of fatigue, when a posture is maintained for a prolonged period of time, the muscles relax and the vertebrae sag against the ligaments which provide a rigid check against further motion. Control of extension of the lumbar spine is provided by the anterior abdominal muscles and exten-

sion is limited by the anterior longitudinal spinal ligament (fig. 3). This restraint becomes important during relaxed standing when gravity holds the lower lumbar vertebrae extended against the restriction of the anterior longitudinal ligament. Control of flexion is provided by the muscles of the back which have the strength and the endurance to provide adequate support during intermittent activities. The range of lumbar flexion, however, is limited by the posterior ligaments which include the supraspinous ligament running along the tips of the spines of the vertebrae, the interspinous ligaments between the spines, the ligamenta flava running between the laminae of the arches of the vertebrae and the posterior longitudinal ligament running along the dorsal surfaces of the bodies of the vertebrae attached to the intervertebral discs. The fibers of the annulus fibrosus also restrict bending of the vertebrae in any direction although the interspinous ligaments and the supraspinous ligament are more advantageously placed with longer lever arms to restrict flexion. The posterior ligaments are heavy elastic ligaments in the lumbar region. Because of their elastic properties these ligaments provide an increasing resistance as flexion increases as well as providing the final check on forward motion. The lateral motion of the vertebrae is restricted by the fibers of the annulus fibrosus, the lateral vertebral ligament which firmly ties each annulus fibrosus to the vertebra immediately above and below, and the relatively insignificant intertransverse ligaments

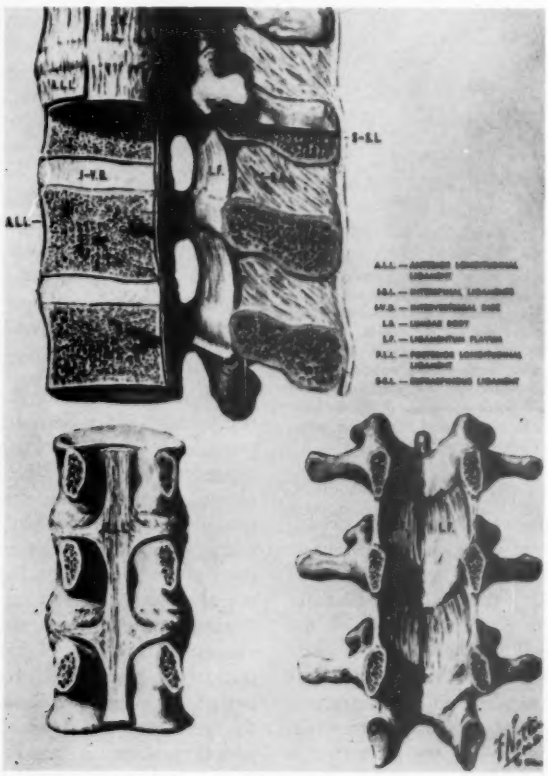

Fig. 3 — The ligaments of the lumbar spine. The ligamenta flava, the interspinous ligaments and the supraspinous ligament are strong elastic structures. ***(Reproduced by permission from Frank H. Netter, M.D., The Ciba Collection of Medical Illustrations, Volume I, Nervous System.)***

running between the transverse processes.

Injury to the low back may be caused by two types of stresses, compressive stresses or tensile distracting stresses. The comprehensive stresses are exerted on the vertebral bodies, the intervertebral discs, or the apophyseal joints and pedicles. Under normal conditions of health and nutrition it is only the extremely severe compressive stresses such as may occur with severe trauma that will exceed the compressive strength of the bodies of the vertebrae and cause vertebral collapse. However, when metabolic imbalances are produced by chronic inflammation, chronic toxicity, malnutrition, or endocrine imbalance, osteoporosis occurs and the weakened vertebrae may collapse as the result of a relatively mild stress. Today this is especially a problem in the cases of patients who have been on adrenocortical steroids (fig. 4). The sudden, sharp, breathtaking, girdle-like pain produced by excessive pressure on these weakened or collapsing vertebrae is so typical as to be nearly diagnostic. On x-ray, the first evidence of impending collapse is cupping of the superior and inferior surfaces of the bodies of the vertebrae which very shortly may go on to complete collapse.

Compressive stresses on the apophyses cause wear of the apophyseal cartilages and after prolonged wear produce osteoarthritic changes and pain. Since the compressive stress on the apophyseal joints is related to the angle of the sacrum, postural exercises to decrease the inclination of the pelvis are helpful in diminishing this problem.

Compressive stresses exerted on the intervertebral discs increase the hydraulic pressure within the disc and exert bursting or tensile stresses on the fibers

Fig. 4 — Osteoporosis developing in a 69-year-old woman after prolonged treatment with cortisone and resulting in concavity and collapse of thoracic and lumbar vertebrae. The developing concavities of the epiphyseal plates of the bodies of the vertebrae are early signs of impending vertebral collapse.

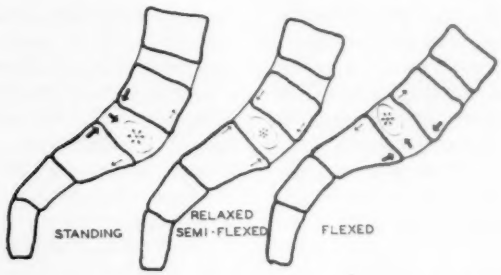

Fig. 5 — External pressures on an intervertebral disc produce an internal hydraulic pressure transmitted in all directions. This hydraulic pressure, which exerts a bursting tension on the annulus fibrosus, is least in the relaxed mid-position and increases when the lumbar spine is extended or flexed.

of the annulus fibrosus (fig. 5). When the lumbar vertebral column is in the midposition, the pressures within the discs are least. On bending of the vertebral column in any direction the superimposed force produces a hydraulic pressure within the disc exerted in all directions which must be counteracted by the tensile strength of the fibers of the annulus fibrosus. It is this hydraulic pressure which causes the rupture of the annulus fibrosus and the protrusion of the nucleus pulposus when an intervertebral disc herniates. The annulus fibrosus must have flexibility in order to allow motion to occur in the intervertebral disc. Over a period of years the annulus and also the nucleus pulposus become relatively less supple and respond to distortion more slowly. If there has been previous injury to the annulus with healing by fibrosis, flexibility is impaired further so that the annulus is more susceptible to tearing during bending.

In addition to the compressive stresses caused by motion of the lumbar spine, tensile stresses also are exerted on muscles and ligaments. During normal movement short of the limit of motion these stresses are counteracted by contractions of the muscles of the trunk. In ordinary activities when the trunk is moved frequently, the support is provided by muscular contraction to maintain stable balance. Under circumstances in which one position is maintained for a period of time, the muscles relax and the balance is maintained by tension against the ligaments or by external support.

During relaxed standing the lower lumbar vertebrae are in a position of maximal extension, held in check by the anterior longitudinal ligament of the spine (fig. 6). It is only in the upper lumbar vertebrae and at the thoracolumbar junction that further extension of the lumbar spine is possible during relaxed standing.

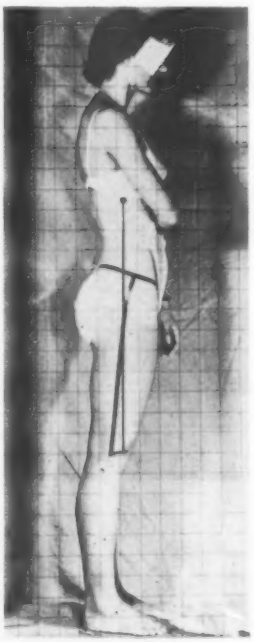

Fig. 6 — In the normal relaxed standing position gravity holds the lumbar spine, hip and knee extended against restricting ligaments. The lower lumbar spine is restricted against further extension by the anterior longitudinal ligament. The hip joint is restricted by the iliofemoral ligament and the knee joint is restricted by the collateral and cruciate ligaments.

A greater strain on the lumbar ligaments occurs under conditions of flexion which are usual to daily existence. Because most activities occur in front of a person and are carried out while sitting, flexion of the spine is a frequent position (fig. 7). During sitting in an ordinary straight chair with the knees flexed, the lumbar spine is flexed far ahead of the normal relaxed position.

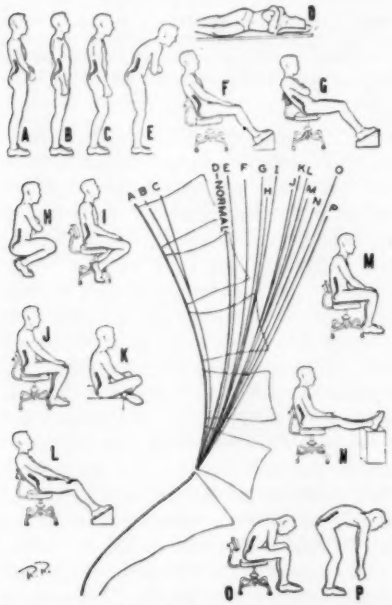

Fig. 7 — Variations in flexion of the lumbar spine with posture. The normal relaxed position in which forces for flexion and extension of the lumbar spine are equal is the position assumed when a person lies relaxed on his side with the hips and knees flexed to 135 degrees. The lumbar curve for this position is marked D. All sitting positions with or without support cause flexion of the lumbar spine from the relaxed position. *(Reproduced by permission from J. J. Keegan.[1])*

Posterior rotation of the pelvis occurs during sitting due to the tightness of the iliotibial fascia and the extensor muscles of the hip. Keegan[1] observed that the normal relaxed position of least tension around the hip joint and knee joint was when both joints were flexed to 135 degrees. In that position the elastic tensions on the flexor and extensor sides of the hip and knee joints were equalized. This is the position of comfort which a person assumes when he is lying on his side. It is also the position of comfort which a person attempts to assume when semi-reclining in an easy chair. This position of the lower extremities appears to produce the neutral position of relaxation in the lumbar spine. During standing the lumbar spine is extended considerably beyond this neutral position. During sitting the lumbar spine is flexed forward from this position. As the knees are extended, the iliotibial fascia on the posterior and lateral surfaces of the thigh is put under greater tension and rotates the pelvis backward, flexing the lumbar spine. Flexion of the knees relaxes the iliotibial fascia and the long extensor muscles of the hips and allows the pelvis to be rotated more anteriorly. Many adults have a limitation of straight leg raising to approximately 120 degrees and consequently cannot sit on a flat surface with the knees extended and the pelvis fully erect. It may be observed that the angle measured on straight leg raising will be the angle assumed between the femur and the pelvis in the long sitting position. If this angle is only 120 degrees it means that the pelvis is 30 degrees short of the upright position and consequently maintenance of the upright posture depends on flexion of the lumbar spine. This angle cannot be diminished by providing external support to the sacrum and/or the back.

To prevent the transmission of tension from the extensors of the hip upward through the extensor ligaments of the lumbar spine, it is essential that adequate support be supplied to the pelvis to prevent posterior rotation when a person is sitting. Such support must be applied to the wings of the ilia and to the sacrum below the level of the lumbosacral junction (fig. 8). The back of an adequate posture chair should provide supporting pressure against the gluteal muscles and the ilia as well as against the upper part of the sacrum. This support should be extended upward behind the lumbar spine to provide stability for the back so that the lumbar muscles need not be used for balance. However, the major support for the pelvis which resists the tension of the hip extensors and iliotibial fascia should

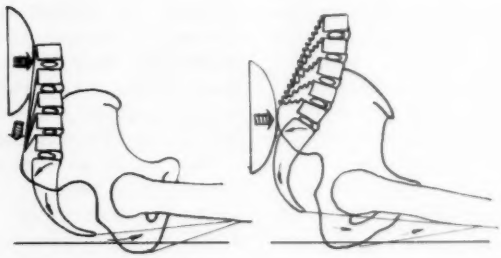

Fig. 8 — During sitting without back support or with support supplied to the thoracic or upper lumbar spine, the pelvis is rotated backward by the pull of the posterior ligaments, fascia and muscles of the thighs, and the posterior lumbar ligaments are put on stretch. If support is provided to the pelvis posteriorly this counteracts the posterior rotation of the pelvis and the posterior lumbar ligaments are relaxed.

be provided by the support against the upper portion of the pelvis itself. In order to achieve this support, the back rest should begin no more than four inches above the chair seat and should extend to the upper lumbar level. The chair back should have a concave profile in the transverse plane in order to support the ilia as well as the sacrum and should have a slightly convex profile in the sagittal plane in order to provide adequate lumbar as well as pelvic support. Sitting postures in which the knees are extended will exert more tension through the iliotibial band to rotate the pelvis posteriorly and flex the lumbar spine than will sitting postures in which the knees are flexed. If the support from the back of the chair is applied behind the thoracic or the upper lumbar area rather than behind the pelvis, the tension to counteract posterior rotation of the pelvis is transmitted through the lumbar muscles and ligaments. When the erector spinae relax flexion of the lumbar spine occurs and this tension is transmitted through the posterior lumbar ligaments.

The design of modern over-stuffed furniture is responsible for many backaches. The free length of the thigh from the posterior buttock to the popliteal space when a person is sitting with the knees flexed to 90 degrees is not more than 16 inches. Therefore, in order that a person may sit with his pelvis fully supported against the back rest, it is necessary that the seat of the chair not be more than 16 inches long and that the contouring of the seat be such that gravity assists in holding the pelvis firmly against the back of the chair. In over-stuffed furniture which is constructed with the seat longer than 16 inches a person cannot flex his knees to 90 degrees when his pelvis is resting firmly against the back of the chair. Usually a person slumps in such a chair with his back supported at the midthoracic level, his lumbar spine flexed and his knees partially extended. This position stretches the posterior lumbar ligaments during the time of sitting. Even if the seat does not exceed 16 inches in length the soft cushioned back of the chair does not provide adequate support to prevent posterior rotation of the pelvis and flexion of the lumbar spine.

The modern automobile seat has all of the defects listed above. The seat is usually too long. The distance from seat to floor is not great enough so that the knees can be flexed to relax the hip extensors. The cushions are too soft to provide adequate support for the pelvis. The major support for the back is provided at the midthoracic level rather than at the level of the pelvis. All of these factors promote lumbar flexion and strain. In addition to this, the jouncing of the car during motion is responsible for repeatedly increasing the flexor stress on the lumbar spine. It is not surprising, therefore, that many people complain of backache after riding in cars. Corrective measures such as a pad behind the low back and pelvis to give additional pelvic support and to shorten the length of the seat, or a firm rather than a softly cushioned seat with firm support behind the pelvis often will

relieve the backache which develops while riding in a car. It would seem that a properly designed seat would alleviate this type of backache.

Forward bending produces the greatest amount of lumbar flexion. There is very little difference in the angle of flexion of the lumbar spine whether the knees are flexed or straight. However, bending from the waist with the knees straight provides greater stress on the lumbar spine, because the center of gravity is farther from the lumbosacral junction. When a person flexes at the hips with the knees straight and with the arms hanging from the shoulders, the center of mass of the trunk, head and extremities is eight to 10 inches in front of the lumbosacral junction, and, for a person of average size (140 pounds) the torque at the lumbosacral junction will amount to 600 to 700 inch-pounds even though no additional weight is lifted.

If a weight of 10 pounds is lifted in this position an additional torque of 150 inch-pounds is added. It may be seen that under normal circumstances the force exerted on the lumbosacral junction by the crane arm (the trunk) greatly exceeds the torque due to the external load lifted. However, if the person attempts to lift a heavy weight in the arms, the lumbosacral torque becomes enormous. If 50 pounds is lifted the additional torque is 750 inch-pounds. As a rule when a person attempts to lift a heavy weight he anticipates the work to be done and contracts his muscles accordingly to prepare for the lift. On the other hand when lifting light weights or when bending without any external load, he is inclined to be negligent. If a person holds a flexed position for any period of time, his muscles relax and all of the stress is exerted on the lumbar ligaments. Because he does not prepare himself consciously for the exertion associated with bending without weight lifting, he exposes the ligaments of the back to severe stress which may cause tears. Therefore, it is not surprising that nearly as many people injure the low back when bending without lifting heavy weights as those who develop injuries while they are lifting heavy weights. Once a ligament is torn, it may remain weak and be exposed to further tears during subsequent stresses.

Another prolonged postural stress which commonly is associated with backache is the posture in bed. Many persons have as much trouble with backache developing during the time that they are lying in bed as they do during the day when they are up. Among older adults morning stiffness and low back pain are so common as to be beyond comment. Again this appears to be the problem of prolonged stretching of lumbar ligaments resulting in pain. If the bed sags, the iliotibial fascia is on tension whether the patient is lying supine or on his side. This tension is transmitted to the pelvis, causing pelvic rotation and transmitting the tension to the lumbar ligaments. When a patient lies on a firm mattress placed over a bedboard there is less iliotibial tension and less distortion of the lumbar spine. Possibly, another factor of importance is that a person lying on a firm bed will shift his position more frequently during sleep in order to relieve the pressure points in contact with the firm mattress and therefore will not be exposed to as prolonged stretching of the lumbar ligaments as when he is sleeping on a soft mattress and moving less frequently.

It is not clear whether or not congenital anomalies play an important role in the problem of backache. The incidence of congenital anomalies is so high that statistics are difficult to interpret. A recent study by Crow and Brogden[2] of 936 young men who were applicants for Air Cadet or Air Force Academy training, showed an incidence of 38 per cent with spina bifida occulta, 21 per cent with previous Scheuermann's disease, 12 per cent with transitional vertebrae in the lumbosacral region, six per cent with spondylolysis, and five per cent with spondylolisthesis. Only 40 per cent of these young men had no variations from the "normal" spine. With such a high incidence of anomalies, it becomes extremely difficult to correlate backache with the presence of an anomaly.

Inflammatory reactions in the body may have an effect on the sensitivity of ligaments to strain. It has been demonstrated that periarticular inflammation will decrease the tensile strength of ligaments and periarticular connective tissue to less than 50 per cent of the normal strength.[3] In addition to this there are indications that the systemic response to inflammation may result in a decrease in the tensile strength of ligaments. The coincidence of low back strain and backache, without traumatic onset, associated with upper respiratory infections or with gastrointestinal infections is highly suggestive.

Muscular strength is protective against back strain during ordinary activities. With an increase of strength endurance is increased and fatigue occurs more slowly. Rested and strong muscles support the lumbar spine during activities which require bending. They relax only when the body assumes a relaxed position. However, during prolonged bending, as fatigue occurs, the extensor muscles of the lumbar spine relax and the stress is borne by the ligaments. Stronger muscles have greater endurance and fatigue more slowly than do weak muscles. Therefore, persons with good strength in the muscles of the back are less likely to relax during bending and have less likelihood of ligamentous strains. Because periodic exercise during adult life helps to maintain strength and endurance it protects the back against the sprains which occur from excessive stress on the ligaments of the back during fatigue.

Evaluation of the Patient with Low Back Pain

In the evaluation of the patient with low back pain the area of involvement and the type of injury should be localized as specifically as possible. There are, in general, four types of conditions which should be differentiated; bony injury, injury to joints, compression of nerve roots, and injury to other soft tissue. Diagnosis of vertebral fractures or compression is made by x-ray. Appropriate x-rays should be taken in all cases of backache to rule out bony or articular damage as well as to provide information concerning bony relationships.

A diagnosis of involvement of a nerve root or of a herniated lumbar intervertebral disc in the absence of depressed reflexes, hypesthesia, motor weakness, or atrophy must be made with reservation. Electromyography provides a good objective test of involvement of the motor roots but gives no information regarding sensory roots. The other signs of the "intervertebral disc syndrome" — the type and onset of pain, the localization or radiation of pain, the tenderness, the limitation of spinal motion, the limitation of straight leg raising — may occur with other injuries to the lumbar area and are not diagnostic of compression of a nerve root. Following the description by Barr and Mixter[4] of the herniated intervertebral disc with compression of the lumbar nerve roots, the diagnostic pendulum swung toward the diagnosis of most low back and sciatic pain as being due to compression of a nerve root. Enthusiasts reported that up to 95 per cent of all backaches were due to this cause. With the passage of time and the collection of more data the pendulum now returns toward normal and it is recognized that only a small proportion of patients with backache have a herniated intervertebral disc. Menser and Duvall[5] recently reported that of 525 cases of low back pain, in only 17 per cent were the symptoms attributed to the lumbar intervertebral disc syndrome, although 47 per cent reported pain referred down one or both lower extremities.

Referred pain into the lower extremities cannot be used to differentiate irritation of a nerve root from irritation of terminal nerve endings in the soft tissues of the back.[6-8] Deep pain is poorly localized in a segmental distribution. The projection of deep pain appears to be made on the basis of segmental sensory stimulation and is not dependent on direct irritation of fibers from the area to which the pain is projected. Because of the multisegmental innervation of the mesodermal structures in the low back and lower extremities specific localization on the basis of referred pain is rarely possible.

The posture and mobility of the unclothed patient should be studied in the standing position. Inspection of the back while the patient is standing may show asymmetry of the back, inequality of the height of the iliac crests, inability to stand fully erect or to stand relaxed with hips and knees extended, flat back, lordosis, or kyphosis. The patient should be asked to bend forward at the hips to the extent possible without the production of pain and to straighten again. Observation of the curve of the spine during flexion and during straightening should be observed. A protective scoliosis may develop on flexion which is not seen when the patient is standing erect. The patient may have more pain on attempting to straighten his back than he did during flexion. It may be observed that the patient will flex his knees when he attempts to return to an upright position to protect the back against extension. The ability to carry out lateral bending, rotation, and rotation combined with flexion in either direction should also be observed. Palpation of the lumbar back while the patient is standing may elicit tenderness or muscle spasm in the back.

While the patient is sitting on the examining table with his knees flexed to 90 degrees, the posture is again examined for evidences of spinal asymmetry both when relaxed and when moving through the possible ranges of motion. Patellar, Achilles, and Babinski reflexes are tested.

While the patient is lying prone, the back is inspected for asymmetry. The entire lumbar back, buttocks and posterior thighs are palpated for tenderness and muscle spasm. Palpation can be performed more effectively if the skin is lubricated with mineral oil. The interspinous areas, lumbosacral junction, and the sacroiliac joints are carefully palpated for tenderness. The paravertebral, gluteal, and posterior thigh and calf muscles are palpated for muscle spasm or nodules as well as for deep tenderness. Deep tenderness over the sciatic notches is tested. The hips are tested individually and together for pain on forced extension. The back is checked for pain on active or active assistive hyperextension. Tightness or pain in the quadriceps femoris or pain in the lumbar spine is tested with the Ely test.

With the patient lying supine, the posture again is inspected for asymmetry, pelvic obliquity, hip abduction or adduction. The thighs and calves are inspected and measured for atrophy. Discrepancy in circumference of more than one centimeter between the two extremities may be significant. The flexion of the hips is measured both with the knee flexed and with the knee extended (straight leg raising). The limit of straight leg raising in the adult varies from approximately 120 degrees to 100 degrees with discomfort behind the knee when the limit of flexion is reached. If there is a marked increase of pain when the foot is dorsiflexed, this suggests direct sciatic irritation due to stretching. Pain in the back when the thigh is flexed on the chest with the knee flexed, suggests ligamentous injury rather than rootlet irritation. Straight leg raising may cause pain in the back and/or down the legs because of flexion of the back rather than stretch of the sciatic nerve. Ability to flex, externally rotate and abduct the hip (Fabere sign) without pain, rules out pain due to pathology in the hip joint, although the extreme external rotation and abduction may rotate the pelvis on the lumbar spine and cause pain in the back.

In addition to studying the mobility of the lumbar spine in the course of testing hip motion, further tests of mobility are directed at the lumbar spine itself. Simultaneous flexion of both thighs onto the chest is attempted while the knees are flexed; with lumbosacral or lumbar injury, this usually cannot be accomplished because of pain. The flexed knees are draped over the examiner's forearm, the patient's pelvis is lifted slightly from the examining table and the lumbar spine is flexed laterally to right and left to test motion when weight bearing on the lumbar spine is eliminated. Likewise, with the knees flexed the pelvis is rotated to right and left to test the range of rotation. The Gaenslen test for

sacroiliac irritation is performed by having the patient hold one flexed knee to his chest while the contralateral hip is fully extended. In the presence of sacroiliac disease, this produces severe pain in the sacroiliac region. Sensory evaluation of touch, pin prick and vibration is carried out systematically to determine any segmental deficiencies.

The manual test of the strength of muscles is of value in eliciting segmental muscular weaknesses. The hip flexors and adductors are innervated from the second and third lumbar segments; the quadriceps receives its innervation from the third and fourth lumbar segments. The anterior tibial muscle receives its innervation from the fourth lumbar segment. The peroneus longus and brevis receive their innervation from the fifth lumbar and the first sacral segments. The extensor proprius hallucis receives its innervation from the fifth lumbar segment, the hamstrings and gluteus maximus from the fifth lumbar and the first sacral segments and the flexors digitorum and gastrocnemius from the first and second sacral segments. It must be remembered that pain may prevent the patient from performing strong contractions with muscles which are not weakened by compression of their motor nerve roots. A sensory deficit or specific motor weakness is diagnostic of nerve root compression. Electromyography provides objective confirmation of involvement of motor nerves.

X-Ray Evaluation

X-ray studies should be made routinely on all patients with backache. The standard anteroposterior and lateral x-rays generally will show the bony conformation and the intervertebral spaces. A spot film may be necessary to show the details of the lumbosacral junction. An anteroposterior view directed 30 degrees to 40 degrees cephalad in the plane of the superior surface of the sacrum is necessary to show the lumbosacral interspace. X-rays taken in the upright position will emphasize lordosis or scoliosis due to the weight of gravity. Oblique x-rays in the planes of the apophyseal joints provide information regarding malposition or arthritic changes in these joints.

In addition, functional x-rays of the limits of motion frequently are helpful in localizing the area of trauma. Hasner, Schalimtzek and Snorrason[9] have reported that functional x-rays demonstrated abnormal lumbar vertebral motion in two-thirds of their patients with lumbar or sciatic pain although routine x-rays showed abnormalities in only one-third of these patients. Anteroposterior x-rays with the patient standing and bending laterally as far as possible show the motion between adjacent vertebrae. In a normal back during lateral bending there is observable wedging of the intervertebral discs on the side toward which the patient bends and widening on the opposite side. At the level of the injury, however, because of muscular splinting, fibrosis, or structural changes, the amount of wedging is reduced. In some cases it may be found that there will be paradoxical deviation of one vertebra in the opposite direction (fig. 9).

Motion in the anteroposterior plane also is studied. The patient sits on the edge of a bench or stool to stabilize the pelvis and lateral x-rays are taken in full flexion and full extension (fig. 10). At the level of injury motion may be reduced

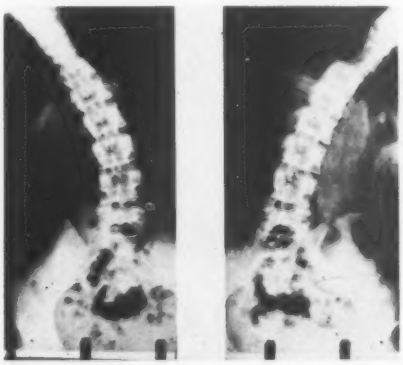

Fig. 9 — During lateral bending there is observable wedging of the intervertebral discs on the side toward which the patient bends and widening on the contralateral side. At the level of injury there may be no motion or in some cases paradoxical motion in the opposite direction.

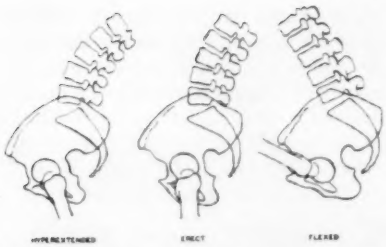

Fig. 10 — X-rays of the lumbar spine during full flexion and full extension normally show uniform curves. At the level of injury the motion may be reduced. Anteroposterior sliding of one vertebra on another of more than two millimeters indicates pathologic hypermobility. These illustrations were traced from x-rays of the back, pelvis, and thighs of a normal 21-year-old woman during erect standing, maximal trunk extension while standing, and maximal trunk flexion while sitting.

or absent. The vertebral bodies are measured from the anterior surface for anteroposterior hypermobility or sliding which has been referred to as primary instability. Anteroposterior displacement of more than two millimeters from full flexion to full extension is considered pathologic. It has been reported that this hypermobility is associated with a split between the annulus and the nucleus pulposus. Menzer and Duvall[5] observed that 13 per cent of 504 patients with backache showed this hypermobility while eight per cent of 94 patients without a history of backache showed this type of hypermobility. Forty-three per cent of their patients with low back pain showed no motion of the fourth and fifth lumbar vertebrae while only 15 per cent of their normal control series showed no motion at these levels.

Treatment

Throughout the discussion of backache the importance of the tensile forces which strain or tear connective tissue has been emphasized. In all cases of backache this type of damage occurs. In the case of fractures there is additional bony trauma to treat and in the case of radicular compression there is the problem of decompression of the nerve root. However, in all cases of backache, proper treatment is necessary to allow for healing of stretched or torn connective tissue. For this purpose therapy can be divided into a few simple categories:

(a) Support
(b) Rest
(c) Analgesia
(d) Anti-inflammatory measures
(e) Restoration of function

When there are tears of soft tissues, healing occurs by the deposition of connective tissue either in a loose areolar network which provides for some mobility or in a dense mat or scar in which mobility does not occur. It is necessary to provide for healing which will not result in restricted mobility in areas in which mobility should be retained but which will allow ligaments to heal with the necessary tensile strength. If support is provided with adequate restriction of motion, healing will occur. This support is provided both to promote the proper healing of the torn connective tissue and for relief of pain.

The normal physiologic method of providing immobilization in an area of injury is for muscular contraction or splinting to occur in the muscles surrounding the area preventing motion in the torn connective tissue. Although this muscular splinting does limit motion it leads to the secondary development of pain. Muscles which remain contracted for a prolonged period of time interfere with their own circulation and cause the accumulation of intramuscular metabolites which results in edema and pain in those muscles. Any motion which causes pain results in this muscular splinting with its concomitant secondary pain. Adequate support allows muscular relaxation while recovery can progress.

For the patient with an acute backache, bed rest is the most satisfactory means of support and rest. Especially in injuries to intervertebral discs, bed rest is important because the weight of the body causes significant compression of the damaged discs and interferes with normal healing.[10] The patient should lie on a firm mattress over a flat bedboard. To provide further stability and allow for muscular relaxation, traction applied with a pelvic belt is desirable (fig. 11). Ten to 25 pounds of traction is adequate for relief of pain. The foot of the bed is elevated three inches to provide counter-traction. If the traction

is increased beyond this amount the patient will develop a backache due to fatigue of the erector spinae muscles. Pelvic traction is far more comfortable than leg traction. The patient can lie on his back or side as he wishes while the lumbar spine is stabilized by the moderate traction so that he has less pain. For the patient with an acute backache it is essential that he not sit nor stand for several days while the initial healing begins. Following that, he may be allowed up once a day for bathroom privileges but remains reclining and in traction the rest of the time. In our experience, pain usually diminishes within 24 hours and is gone in four to six days.

Physical therapy is used to counteract the inflammatory reaction in the back. Adequate deep heat provided by diathermy at low intensity increases circulation to the muscles and possibly also to the damaged ligaments. Twenty minutes of diathermy followed by deep stroking and kneading massage to the muscles of the lumbar back, buttocks and hips to aid lymphatic and venous return and to relax the muscles, makes the patient more comfortable. This treatment daily or if possible, twice daily, is of considerable value in restoring the patient to normal mobility.

Although the patient has received relief from his backache and has had some return of motion in his back again, it must be remembered that these tears are not entirely healed and that he is subject to reinjury by any excessive strain. It must be kept in mind that the chronic strain from prolonged sitting or from bending is likely to tear the newly formed connective tissue, particularly since he now has restricted motion in that area. For this reason, patients are fitted with a back support to protect them against excessive motion during normal daily activities. As a general rule a canvas corset with rigid back steels is prescribed for these patients (fig. 12). An adjustable side-lacing corset is preferred for the average patient. This provides adequate support for the back to restrict flexion or extension. It is inexpensive. It is a stock item which can be fitted immediately. It provides adequate support so that the patient is able to carry on ambulant and sedentary activities. Usually patients will need to

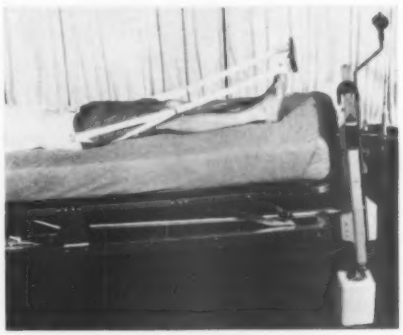

Fig. 11 — Pelvic traction of 10 to 25 pounds stabilizes the lumbar spine and allows the patient to relax. The foot of the bed is elevated two to four inches for countertraction. The pulley should be approximately 18 inches above the mattress so that the traction rotates the pelvis backward and maintains the lumbar spine in the neutral position (fig. 7).

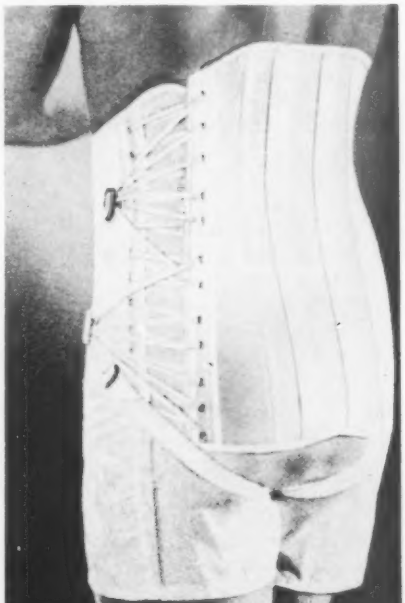

Fig. 12 — A canvas corset with rigid back steels is prescribed for patients with injuries to the low back. An adjustable side-lacing corset is an inexpensive stock item which can be fitted immediately. The corset should fit snugly about the hips and extend up to the level of the tenth thoracic vertebra. Peroneal straps (or garters on women's corsets) are necessary to keep the corset from riding up.

wear this corset for a minimum of three months and sometimes four to six months. At the end of that time the patient can begin to go without the corset during light activities but should wear it during more vigorous activity. Eventually most patients find that they can discard the garment. Some patients find that they have enough instability in the back so that they need to continue wearing their corsets at all times for protection against aggravation of the back strain.

For some patients a chair back brace appears to provide greater stability for the back. This is a somewhat heavier device which is custom-made to fit the needs of the patient. The Williams back brace was developed as a corrective brace for lumbar lordosis. It does not provide the same stability against flexion that the corset or chair back brace provides although it is an effective support against hyperextension. It is used in selected cases where extension appears to be the only motion which causes pain or when attempting to correct a marked lumbar lordosis.

Additional pharmaceutic treatment for backache is worthy of comment because of the multitude of compounds which are advocated for relief of muscular pains or muscular spasm. In our experience the only compound which is of particular value in backache is acetylsalicylic acid or one of its derivatives. This is prescribed for patients in amounts up to tolerance. If the patients have trouble with gastritis, a buffered preparation is prescribed. Six hundred milligrams four to five times per day is the usual dosage. Pharmaceutic compounds other than narcotics, advertised as spasmolytic, lissive or analgesic, have appeared to be of no value in our hands, even when given in quantities large enough to produce somnolence, vertigo or other side reactions. With the management described above, narcotics have rarely been necessary.

The exercises prescribed in the treatment of low back pain vary depending on the type of injury. For patients who have a lordosis with low back strain, exercises to improve the posture will relieve the strain and pain. The muscles to be strengthened are the abdominal and the gluteal muscles. All exercises are begun moderately and increased in intensity as the strength and endurance of the patient increases. Backward rolling of the pelvis to flatten the lumbar spine is carried out with the patient supine. Unilateral and bilateral straight leg raising and sitting-up exercises strengthen the abdominal muscles. Unilateral hip extension with the patient supine strengthens the hip extensors. Bilateral hip extension is a vigorous exercise for the hip extensors and erector spinae. For patients with osteoarthritis, hyperextension exercises frequently cause aggravation of back pain and the patient should be so positioned that he can carry out these exercises from a position of moderate hip flexion to full hip extension without hyperextension of the lumbar spine.

For the young individual who has recovered from his injury but still has limited mobility in his back, progressively more vigorous stretching exercises will help him regain his suppleness and will diminish the likelihood of further injuries from tears of tight connective tissue. Flexion, extension, lateral bending and rotation calisthenics serve to increase mobility and strength. Older individuals do not regain mobility readily and vigorous attempts to carry out stretching exercises may only serve to re-aggravate the injury. For this reason, mobilizing exercises are prescribed more cautiously for older patients. Patients with arthritic changes also respond adversely to prolonged or vigorous exercise programs. They can regain muscular strength by short sequences of progressive resistance exercises or by the application of brief maximal muscular contractions within the free range of motion.

Before a patient may safely discontinue the use of his corset or brace he must have regained his muscular strength through systematic exercise. During the time that he is wearing the support he will maintain muscular strength only if he is exercising properly. These exercises within the free range of motion provide

the stimulus to maintain muscular bulk and strength without re-injury to the damaged connective tissue. As the muscular strength increases, the endurance is increased and the patient has less likelihood of re-injury.

Summary

Injury to the low back may be due either to a sudden extreme force which exceeds the compressive strength of bone or the tensile strength of ligaments and connective tissue, or to a prolonged stress which stretches ligaments and connective tissue and causes pain. In normal daily activity high tensile stresses are exerted against the ligaments and connective tissues in the low back. During periods of quiescence the muscles relax and support for the vertebral column is provided by the ligaments. Prolonged stress on these ligaments causes strain and pain. Under abnormal conditions of metabolic imbalance or inflammation the strength of bone and connective tissue is diminished and injury may occur as a result of mild stress. Improper or inadequate support during bending, sitting or reclining may produce prolonged stresses which will injure these supporting tissues. Proper support during sitting is especially important.

Evaluation of the patient with an injury to the low back must be thorough to establish whether there is injury to bone or joints, or compression of nerve roots. In all cases there is injury to connective tissues. The site of injury should be localized as definitely as possible by physical examination, functional tests and roentgenologic studies. Electromyography is useful to establish involvement of motor nerve roots.

Adequate therapy includes support and rest so that healing can occur, relief of pain, removal of the products of inflammation, restoration of normal mobility and re-establishment of normal strength. Patients must be instructed in proper posture, precautions against back strains during daily activity, and exercises to maintain the mobility, strength, and endurance in the muscles of the back.

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Information relative to securing reprints of this study may be had by checking the Reader Service column on page lv of this issue.

"What a beautiful sight!"

— FREEDOM 7

Electrodiagnosis and Electrical Stimulation in the Treatment of Neuromuscular Disorders

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● By studying the action potential, which reflects the dynamics of nerve trunk excitation, it is possible to determine the parameters of single electric pulses which may serve as the basis for therapeutic electrostimulation. Wedensky established the interdependence between the strength of a tetanic muscle contraction and the pulse frequency of electric stimulation. Anokhin showed that this interdependence is related to the functional state of the nerve trunk and that the frequencies which evoke optimal contraction in electrodiagnosis may be used to treat neuromuscular diseases. Experience has demonstrated that this approach substantially complements method of single pulse stimulation. In clinical practice the author also employs the simpler classical method of galvanic and faradic stimulation for electrodiagnosis. Following a comparative investigation of the two methods on 126 patients with neuromuscular disease the reliability of the simpler test could be validated. In treating neuromuscular diseases with electrical stimulation, preference is shown for exponential pulses in a wide range of frequencies and durations of modulated amplitude. Such pulses are often less painful and cause less fatigue in injured muscles than rectangular pulses. By careful selection of duration and frequency, tetanic contraction could be elicited in impaired muscles even in patients with partial or slight reaction of degeneration. In many instances, especially those with only a partial loss of nerve trunk conductivity, a new method has been used which is called "active stimulation." Active stimulation is achieved by asking the patient to attempt voluntary (natural excitation) contraction of the impaired muscle at the same moment that the stimulating current is applied. In this manner, electrical stimulation facilitates or strengthens the contraction of the weakened muscle. In the author's experience, this method has been more effective in many cases than ordinary rhythmic stimulation.

Electrodiagnosis and electric stimulation play a very important role in the diagnosis and treatment of neuromuscular injuries. From the variety of methods of electrophysiologic examination only the most simple and reliable are apt to be used in clinics.

To make the choice, we shall consider the simplest form of action potential wave (fig. 1). The potential wave reflects the intensity of physiochemical changes, underlying the process of excitation. The wave consists of the two principle phases, the active and the restorative, with the changes going in the opposite directions. As for the active part, it consists of a latent period, *to*, of the preparatory processes and a brief period of maximum intensity, *ts*, called the spike. A critical point, *0*, between the latent period and the spike is of essential importance. If the intensity of the excitation process reaches the value *h*, corresponding to this critical point, called the threshold, the spike takes place and causes the contraction of the muscle. If the intensity of the excitation process does not reach the threshold value the spike and, consequently, the contraction of the muscle do not occur.

The form of the potential wave, the duration of its two principal phases and the threshold value depend on the state of the nerve trunk and so is characteristic of its injury.

To excite effectively the injured neuromuscular unit with an electric stimulus it is necessary to maintain the intensity of the excitation process on a level not lower than that required for the formation of the spike. For the most simple rectangular and triangular electric pulses this condition requires that (fig. 2): (a) the intensity of the current (the amplitude of the pulse) should not be less than the threshold value *h*; (b) the duration of the pulse should not be less than that of the latent period *to*, and (c) only for triangular pulses, the rate of rise of the leading edge of the pulse ($tg\alpha$) should not be less than the ratio between the threshold *h* and the duration *to* of the latent period: $tg\alpha = \frac{h}{to}$

Thus by ascertaining the most effective intensity, the rate of rise of the current for the triangular pulses in different motor points, and especially the duration of the current flow for the rectangular, it is possible to determine the place and the severity of the nerve injury. All this proves that pulses of the most simple form — rectangular and triangular with a sufficiently wide range of the changes in their intensity, duration and rate of rise — may be used effectively for electrodiagnosis in clinical practice.

The deficiency of the above mentioned method lies in the fact that it implies

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Read at the 3rd International Congress of Physical Medicine, Session on Electromyography, Washington, D. C., August 23, 1960.

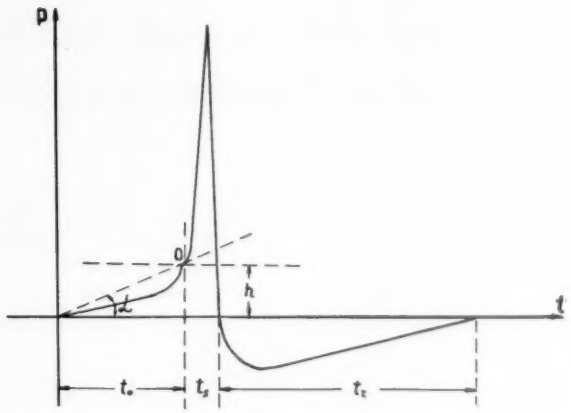

Fig. 1

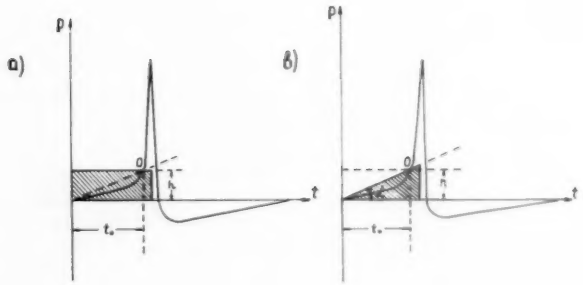

Fig. 2

use of the single pulses, whereas all natural processes of excitation are of rhythmic character.

In the last years of the previous century, N. E. Wedensky found out that the tetanic contraction of muscles depends on the frequency of electric pulses and may be either optimal or minimal in strength.

The diagram (fig. 3a) shows a case when the frequency of the electric pulses corresponds to the rate of alternation of active and restorative phases of a natural excitation process, that provides an optimal contraction. On the other diagram (fig. 3b) the frequency of the pulses exceeds the natural rhythms and and as a result the following pulses fall on the restorative phase and therefore disturbs the normal course of the excitation process. This provides a minimal contraction.

In his special studies for electrodiagnoses, Peter K. Anokhin proved that the corresponding frequencies of the optimal and minimal contraction depend on the functional state of the nerve and consequently may serve as data of electrodiagnosis for injured neuromuscular units.

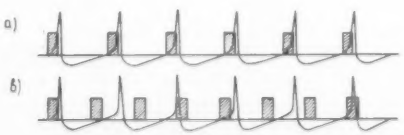

Fig. 3

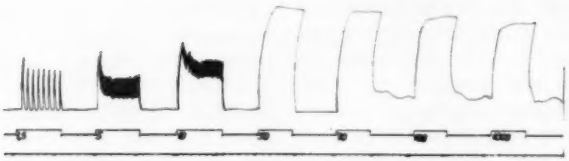

Fig. 4

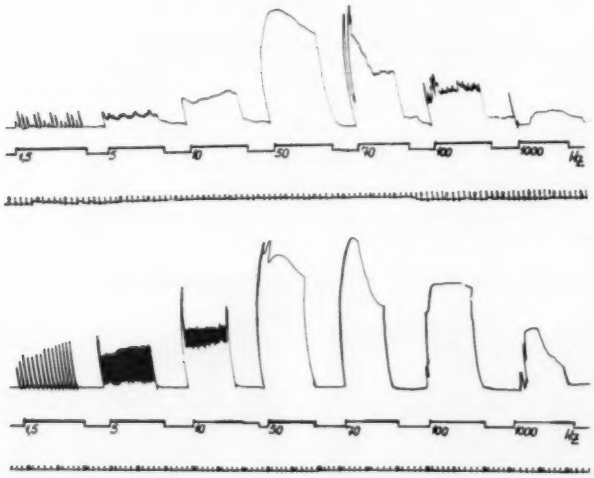

Fig. 5

According to this method, investigation is carried out with the help of recording the contraction of one of the muscles innervated by the injured nerve (figs. 4 and 5). Figure 4 shows the record of an intact muscle; the upper trace, a record of the flexion of a foot in the case of stimulation of the tibial nerve; the middle trace, marks of stimulation and corresponding frequencies, and the lower trace, marks of time. Figure 5 shows a record in a case of injury. Figure 5, top, was recorded before treatment (note the minimal contraction at the 70; 100 and especially 1000 Hz.) and figure 5, bottom, was recorded after the treatment, with considerable improvement in the state of the neuromuscular unit.

The practical work with the use of this method (M. I. Beresina, J. L. Slavutsky, F. I. Eremenko, Z. K. Manovich and others) shows that this method complements considerably the data obtained with electrodiagnosis with the single pulse stimulation.

For clinical investigation in the U.S.S.R., an electronic stimulator is used most widely (fig. 6). It gives the rectangular pulses with a wide range of durations and frequencies (duration from 0.02 to 100 msec.; frequency from 0.5 to 2500 Hz.) and has a constant current output circuit. With the help of this stimulator it is possible to determine an intensity-duration curve and to obtain the optimal and minimal frequencies.

We also use in clinical practice a simple, but nevertheless a sufficiently reliable, method of electrodiagnosis with galvanic and faradic current, called in the U.S.S.R. the "classic method" of electrodiagnosis. For this method we use a very small portable stimulator (fig. 7) which contains only two electronic valves (thyratrons).

During World War II and the postwar period, surgical treatment of the neuromuscular injuries made it possible to verify directly on operation the data obtained by the classic method of electrodiagnosis. The results of our own studies in that matter are shown in table 1. In the table the data obtained by electrodiagnosis are compared with the state of the nerve trunk as revealed during the operation. The figures in the table signify the number of the corresponding cases. The study was carried out in the neurologic clinic of the State Research Institute of Physical Medicine in Moscow (the data are published for the first time). One hundred and twenty-six patients with fire-arm injuries of upper and lower extremities were examined. On the basis of the clinical investigation

Table 1: State of the Nerve Trunk, as Revealed During the Operation

	Complete Organic Lesion	Complete Functional Lesion	Partial Functional Lesion
Absolute Reaction of Degeneration	19	—	—
Complete Reaction of Degeneration	40	26	—
Partial Reaction of Degeneration	4*	8	11
Reduced Normal Reaction	—	4*	14

*Discrepancies noted; see text.

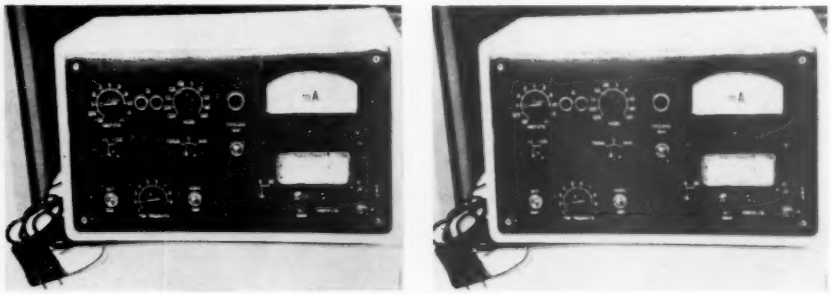

Fig. 6

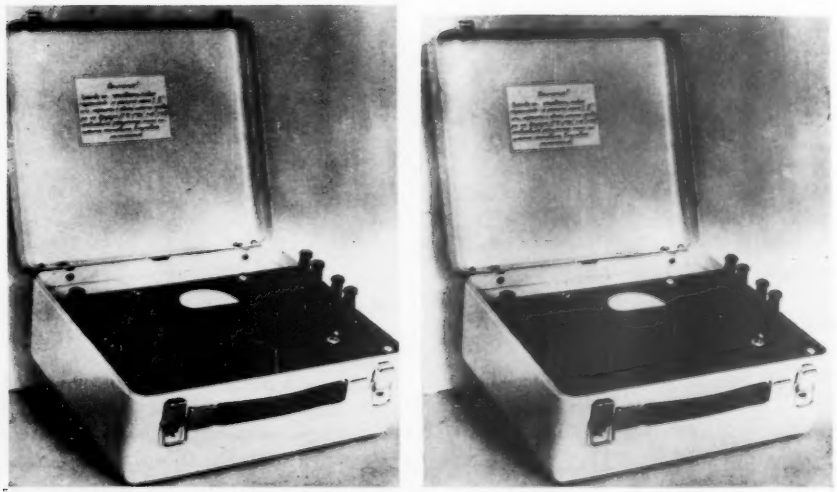

Fig. 7

and the data obtained by the classic method of electrodiagnosis, the clinical diagnosis and the necessity of the operation were determined.

The figures in the table show that in the cases of complete organic lesion and those of only partial functional lesion the data of electrodiagnosis are in conformity with the state of the nerve trunk; it shows either absolute reaction of degeneration or reduced normal reaction. In the cases of partial organic or complete functional lesion the data of electrodiagnosis are in conformity with the severity of injury and show either complete or partial reaction of degeneration. In eight cases only (marked in the table by asterisks) can discrepancies be observed; these occurred when the electrodiagnostic data showed a brighter picture of the state of the nerve trunk. These can be explained by errors committed while carrying out the electrodiagnosis.

In the process of electrodiagnosis we often used the bipolar electrode. This technic ensures an accurate localization of the flow of the electric current. Consequently it gives the possibility of selective stimulation of the injured nerve or muscle which, in many cases, cannot be so easily attained with the unipolar technic.

Effective methods of rehabilitation therapy of neuromuscular injuries were developed in the postwar period. A significant role in these methods is played by physical treatment and especially by the electric stimulation of muscles.

To make the stimulation effective it is necessary to ensure strict correspondence of the electric current's properties to the particulars of excitability of the injured nerve. Therefore, all that was said above about the significance of the duration, rate of rise and frequency of the electric pulses is valid also for the electric stimulation. Our own experience with the electric stimulation indicates that rectangular pulses are often more painful and cause fatigue in the injured muscles. To eliminate these deficiencies we prefer to use the exponential pulses, which are obtained by passing the rectangular pulse through the circuit (fig. 8).

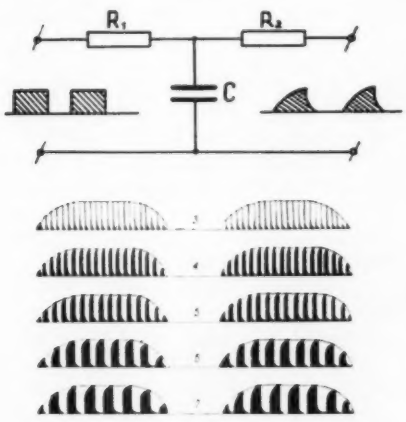

Fig. 8

For the stimulation we use an electronic generator (fig. 9) of the multivibrator type, which produces pulses both of rectangular and exponential form. The duration and frequency of pulses are regulated by 10 steps: duration from 2 to 100 msec., frequency from 100 to 5 Hz. The pulses are surged by an

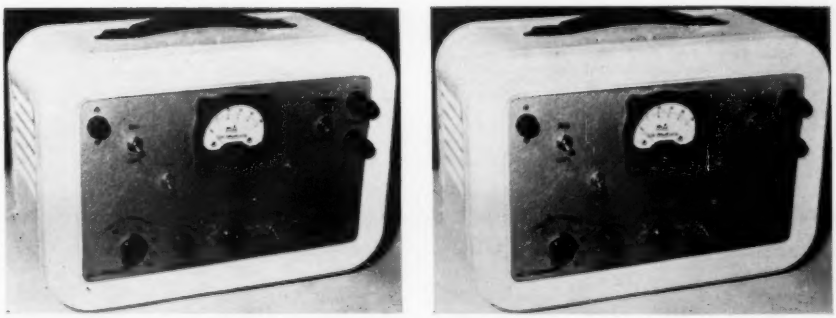

Fig. 9

electronic modulator (fig. 8). The frequency of modulation changes from eight to 48 trains of pulses per minute.

By the proper choice of the duration and the frequency of pulses it was possible to produce a tetanic contraction of the injured muscles even in the cases with the light form of the reaction of degeneration. So, in many cases, especially with only a partial loss of the conductivity of the nerve trunk, we were able to put into practice a new method which we call the active stimulation.

In this method the electric stimulation is combined with the natural impulses of excitation, produced by an effort to the corresponding voluntary movement with the injured muscles. For this purpose during the exercises stimulating current is switched on simultaneously with the patient's efforts to perform the active movements. The stimulation either facilitates or strengthens the contraction of the injured muscles. Our experience with this method shows that the active stimulation has a more favorable effect than ordinary rhythmic exercises. We think that is because in these active exercises some of the central elements are involved; for example, fixation of attention on the contraction of the injured muscles, sending into them the impulses of natural excitation, etc. All this increases the effect of the electric stimulation and reduces the time needed for restoration.

For the active exercises we use the same electronic stimulator in which the rhythmic modulator is replaced by one operated manually or with a pedal. By this modulator the current is switched on and increased in the suitable moments.

Information relative to securing reprints of this study may be had by checking the Reader Service column on page iv of this issue.

Electromyographic Studies in Myopathies and Related Conditions

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Marcos Turner, M.D.
and
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Chicago

● An electromyographic study was done of 53 patients with various neuromuscular disabilities. The study showed: (1) Patients with cerebral palsy were electromyographically normal. (2) Patients with poliomyelitis sequelae demonstrated the typical findings of lower motor neuron lesions, namely fibrillation at rest and primarily polyphasic potentials during effort with an inability to recruit interferential patterns on maximal effort. (3) In pseudohypertrophic muscular dystrophy, dystrophic and polyphasic potentials were most commonly seen during voluntary effort. Myotonic potentials occurred in over one-half of the patients. Fibrillation potentials at rest occasionally occur. It is felt that such fibrillation potentials may represent denervation primarily at the muscle pole as contrasted to the denervation in polio which is primarily at the neural pole. Minimal voluntary effort will generally cause synergistic muscle action with resulting interferential patterns. (4) Facio-scapulo-humeral dystrophy is characterized by electromyographic patterns identical with that of pseudohypertrophic muscular dystrophy except for the absence of myotonic potentials. (5) Amyotonia congenita is characterized by mixed electromyographic patterns, at times similar to that of a polio and at times that of a muscular dystrophy. No myotonic potentials are present. In some patients maximal effort may elicit only simple patterns and in others minimal effort may elicit interferential patterns.

The differential diagnosis of early muscular dystrophy in infancy and childhood may at times be difficult. It involves a consideration not only of other syndromes characterized by hypotonia, such as hypotonia of cerebral, spinal or peripheral nerve origin, but also of the various types of muscular dystrophy, e.g. pseudohypertrophic, facio-scapulo-humeral, amyotonia congenita, etc.

Electromyographic procedures previously have been used in an attempt to classify and to delineate the nature of muscular dystrophy on the basis of neuro-electrophysiologic characteristics. However, the reported results are neither definitive nor constant, especially in the early stages of the disease.

The present study, which describes our observations on the electromyographic findings in muscular dystrophy and in related neuromuscular diseases, is at variance in some aspects with previous reports.

Material

Table 1 lists each of the patients studied by diagnosis and results. Table 2 is a summary of the data in table 1. The case material in this survey consisted of 53 patients, 33 with muscular dystrophy, 11 with polio sequelae and nine with cerebral palsy. Of the 33 patients with muscular dystrophy, 20 were of the pseudohypertrophic type, four facio-scapulo-humeral, and nine amyotonia congenita. The diagnostic criteria were primarily clinical. The muscular dystrophy patients were graded by severity on a 10 point scale, modified from the grading scale of Swinyard, Deaver and Greenspan.[1]*

The polio cases were all of severe degree, being wheelchair or bed-ridden. The interval between the acute onset of the disease and the present study is indicated for each patient in table 1.

The cerebral palsied cases were all quadriplegic and severely involved, unable to ambulate alone. The diagnostic category of each of the cerebral palsied patients, whether athetoid or spastic, is likewise indicated in table 2.

*Grading Scale for Degree of Involvement of Muscular Dystrophy.

1. Walks with slight waddle and lordosis; climbs stairs and curbs without assistance; arises from floor with minimal effort.
2. Needs railings or other support for curbs and stairs; arises from floor with some effort or with slight "climbing up" on self.
3. Cannot negotiate curbs or stairs but can still arise from floor by "climbing up" on self.
4. Unable to rise from floor but can still arise from standard height chair.
5. Unable to arise from standard height chair, but still able to walk on flat surface, over 100 feet.
6. Unable to walk alone over 100 feet and needs wheelchair for getting about.
7. Unable to stand or walk but independent in wheelchair, performing all activities of daily living, including toileting, feeding and bed activities.
8. Able to wheel chair, but needs assistance in bed and toileting activities; has fair posture in chair.
9. Able to wheel chair only a short distance; needs back and side support; scoliosis and other contractures developing.
10. Bed patient; unable to wheel chair; needs maximum assistance for activities of daily living.

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This study supported in part by grants from the Muscular Dystrophy Association and United Cerebral Palsy, Chicago.

Table 1: EMG in Neuromuscular Diseases

Cerebral Palsy	Age in yrs.	Potentials					Patterns: Effort	
		Fibr.	Poly.	Dyst.	Giant	Myot.	Weak	Maximal
Case 1 Spastic	7	—	—	—	—	—	S	I
2 Athetoid	8	—	—	—	—	—	S	I
3 Athetoid	9	—	—	—	—	—	S	I
4 Athetoid	10	—	—	—	—	—	S	I
5 Athetoid	11	—	—	—	—	—	S	I
6 Spastic	13	—	—	—	—	—	S	I
7 Athetoid	14	—	—	—	—	—	S	I
8 Spastic	15	—	—	—	—	—	S	I
9 Athetoid	16	—	—	—	—	—	S	I
Polio Sequelae	**Yrs. After Onset**							
Case 1	5 5	+	+	—	+	—	S	S
2	6 7	—	+	—	—	—	S	I
3	5 8	—	+	+	—	—	S	S
4	1 11	+	+	—	—	—	S	S
5	8 12	—	+	—	—	—	S	S
6	8 13	+	+	—	+	—	S	S
7	14 14	+	—	—	—	—	S	S
8	8 14	—	—	+	—	—	S	S
9	8 15	—	+	—	—	—	S	S
10	8 17	+	+	—	—	—	S	S
11	11 17	—	+	+	+	—	S	S
Myopathies	**Grade No.**							
Pseudohypertrophic								
Case 1	I 5	—	—	+	—	—	I	I
2	III 6	—	—	+	—	—	I	I
3	IV 6	—	—	+	—	+	I	I
4	IV 7	—	—	+	—	—	I	I
5	II 7	—	—	+	—	+	I	I
6	II 8	—	+	+	—	—	I	I
7	IV 8	—	+	+	—	+	I	I
8	III 9	—	—	+	—	+	S	I
9	VII 10	—	+	+	—	+	S	I
10	VII 11	—	+	+	—	—	I	I
11	V 12	—	—	+	—	—	I	I
12	VIII 12	—	—	+	—	+	I	I
13	VIII 14	—	+	+	—	—	I	I
14	VII 15	—	+	+	—	+	S	I
15	VIII 15	—	—	+	—	—	I	I
16	IX 15	+	—	—	—	+	I	I
17	X 15	—	+	+	—	+	I	I
18	IX 16	—	—	+	+	—	I	I
19	IX 17	—	—	+	—	+	S	I
20	X 19	+	+	+	—	+	I	I
Facio-Scapulo-Humeral								
Case 1	I 9	—	—	+	—	—	I	I
2	II 10	—	—	+	—	—	I	I
3	IV 13	—	—	+	—	—	I	I
4	I 28	+	—	+	—	—	I	I
Amyotonia Congenita								
Case 1	VIII 2	—	—	—	—	—	S	S
2	VIII 4	—	—	+	—	—	S	S
3	VII 9	+	—	+	—	—	I	I
4	IX 10	—	—	+	—	—	S	I
5	IX 10	—	—	+	—	—	S	I
6	VII 11	+	+	—	+	—	S	S
7	IX 13	+	+	+	—	—	S	I
8	X 13	—	+	+	—	—	S	S
9	IX 19	+	—	+	—	—	S	I

S — Simple pattern.
I — Interferential pattern.
Grade — Grade I is least and Grade X most involved. See text for detailed description.

Table 2: Distribution of EMG Findings

	Total	Potentials					Patterns: Effort			
		Fibr.	Poly.	Dyst.	Giant	Myot.	Weak		Maximal	
							S	I	S	I
Cerebral Palsy	9	0	0	0	0	0	9	0	0	9
Polio Sequelae	11	5	9	3	3	0	11	0	10	1
Myopathies — Total	33	7	11	30	2	11	12	21	4	29
Pseudohypertrophic	20	2	8	19	1	11	4	16	0	20
Facio-Scapulo-Humeral	4	1	0	4	0	0	0	4	0	4
Amyotonia Congenita	9	4	3	7	1	0	8	1	4	5

S — Simple pattern.
I — Interferential pattern.

Methods

Electromyographic examinations were made with two different instruments — a Meditron Electromyograph with loudspeaker and oscilloscope display, and an assembly consisting of a Grass Model P4 pre-amplifier with DuMont dual-beam oscilloscope. Photographic records were made with a Polaroid camera and with a Grass kymograph motion picture camera. Continuous records of the electrical impulses were also made by means of a magnetic tape recorder.

Both monopolar and concentric bipolar (coaxial) needle electrodes were employed. The monopolar needle electrode consisted of a fine sewing needle (about 0.3 mm. in diameter) insulated except at the tip. The reference electrode for monopolar examination was a surface electrode applied to the skin over the muscle being examined. The coaxial needle electrode consisted of a central insulated wire 0.2 mm. in diameter with an outer sheath 0.5 mm. in diameter.

The muscle chosen for electromyographic examination varied with the patient and the stage and distribution of the involvement. An attempt was made to test at least one of the most involved and one of the least involved muscles. In every patient the following muscles were routinely examined, usually bilaterally: gastrocnemius, rectus femoris, deltoid, and biceps brachii. In addition, other muscles were chosen when indicated. At least two or three electrode insertions were made in each of the muscles examined. The electromyographic findings were classified as abnormal if an abnormal response was elicited during one or more of the needle electrode placements.

Electromyographic recordings were made under the following conditions: *at rest*, with the patient in the position of greatest comfort, usually supine; *during weak voluntary effort*, as lifting a limb against gravity; *during strong voluntary effort*, against manual or mechanical resistance.

The electromyographic observations were defined and classified as follows:

A. Normal Findings

1. *Electrical silence* observed at rest consisted of an isoelectric line without deflections (fig. 1*A*).

2. *Normal motor unit potentials* obtained during voluntary effort, had the following characteristics (fig 1*B*):

Voltage .....300-2000 microvolts (uV)
Duration .....2-10 milliseconds (msec.)
Wave form .....di- or triphasic
Frequency .....3-50/sec.
Sound .....sharp low pitched thump

B. Abnormal Findings

1. *Fibrillation potentials* (fig. 2*A*) present at rest and/or within 10 seconds after needle insertion or mechanical stimulation of the muscle. These potentials are characteristic of denervated muscle.

Voltage .....10-300 uV
Duration .....1-2 msec.
Wave form .....mono- or diphasic
Frequency .....2-30/sec.
Sound .....sharp high pitched click

2. *Polyphasic potentials* elicited during voluntary movement. Typically, these are of long duration (up to 15 msec.) (fig. 2*B*), although in muscular dystrophy they may be much shorter (three to 10 msec.) (fig. 3*B*). These potentials are encountered during the regeneration as well as the degeneration of muscle.

Voltage	50-1000 uV
Duration	3-15 msec.
Wave form	polyphasic (5 or more deflections)
Frequency	2-30/sec.
Sound	rough, low-pitched rasp or rattle

3. *Dystrophic potentials* (fig. 3*C*) elicited by voluntary movement and generally characteristic of myopathies. They are a special type of polyphasic potential of longer total duration and greater frequency, but of lesser amplitude, composed of thinner waves, more sparsely placed. In poliomyelitis they tend to be of shorter total duration and of lesser frequency, and approach the configuration of the polyphasic waves seen in the dystrophies.

Voltage	50-300 uV
Duration of each wave	0.5-1 msec.
Duration of total discharge	5-20 msec.
Wave form	polyphasic
Frequency	10-40/sec.
Sound	rough but high-pitched

4. *Giant potentials* (fig. 2*D*) elicited by voluntary movement; frequently encountered in regenerative stages.

Voltage	2000-5000 uV
Duration	5-15 msec.
Wave form	bi- or polyphasic
Frequency	2-20/sec.
Sound	loud high-pitched

5. *Myotonic potentials* (fig. 3*D*) elicited by voluntary activity, or by tapping the muscle over the needle; consists of a rapid volley of repeated potentials during and after motion or stimulation, and indicates hyperirritability of the muscle fibers.

Voltage	100-500 uV
Duration of each wave	2-5 msec.
Duration of total discharge	0.5-10 sec.
Wave form	repetitive mono- or diphasic
Frequency	50-100/sec.
Sound	"diving airplane" or "motor boat"

C. Patterns

1. *Simple pattern,* usually elicited by weak voluntary motions, consisting of repeated individual motor units, separated from each other (fig. 1*C*).

2. *Interferential pattern,* usually observed during maximal effort, and consisting of a superimposition of motor unit potentials so conglomerate that it is impossible to distinguish individual potentials (fig. 1*D*).

Results

Cerebral Palsy (fig. 1). Normal electromyographic findings were observed in all nine cerebral palsied children examined. At rest, there was electrical silence; during minimal voluntary effort, a simple pattern of normal motor unit potentials was produced; during strong voluntary muscle contraction, many motor units were recruited, resulting in an "interferential" pattern. No abnormal potentials were observed.

Poliomyelitis (fig. 2). In the 11 patients with poliomyelitis sequelae persistent fibrillation potentials were found at rest in five and electrical silence in the remaining six. During muscle contraction, typical polyphasic potentials were found in nine of 11 patients, and thinner polyphasic potentials of the dystrophic type in three. In only one of the 11 patients neither polyphasic nor dystrophic potentials were present. Giant potentials were found in three of the 11 patients, a frequency greater than that observed in the other clinical groups. In response to *maximal* effort, simple patterns instead of interferential ones were paradoxically present in 10 of the 11 patients (fig. 2*E*). Presumably this reflected the severe involvement of this group of polio patients in whom sufficient muscle units could not be recruited to evoke an interferential pattern.

Muscular Dystrophies (fig. 3). In the patients with muscular dystrophy, the most commonly found abnormal potential was the dystrophic one which was present in 30 of the 33 patients examined. The next most common potentials were the

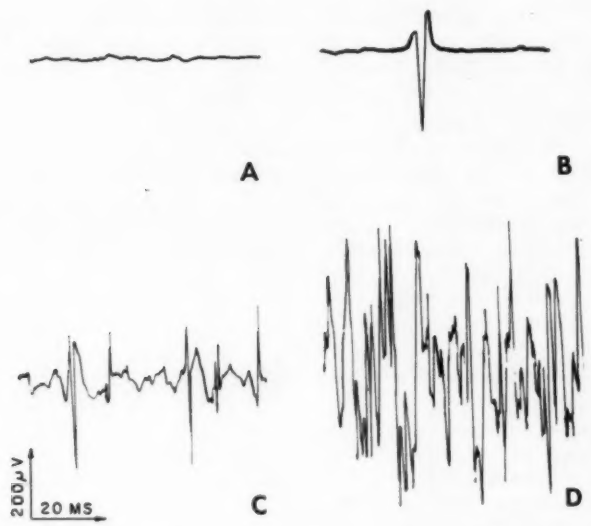

Fig. 1 — Normal electromyographic findings present in cerebral palsied group. *A.* Electrical silence at rest. *B.* Normal motor unit. *C.* Simple pattern of normal motor units evoked by minimal voluntary effort. *D.* Interferential pattern evoked by strong voluntary effort.

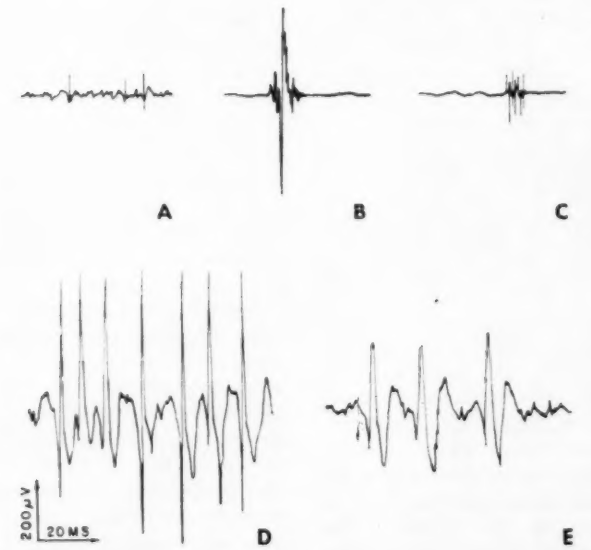

Fig. 2 — Electromyographic findings in patients with widespread severe poliomyelitis sequelae. *A.* Fibrillation potentials present at rest in five of 11 patients. *B.* Polyphasic potentials seen on voluntary effort in nine of 11 patients. *C.* Dystrophic-like potentials seen in three of 11 patients. These potentials tend to have a shorter duration than those in muscular dystrophy. *D.* Giant potentials found in three of the 11 patients. *E.* Simple pattern present after both weak or maximal effort in 10 of 11 patients. Only one patient was able to recruit an interferential pattern.

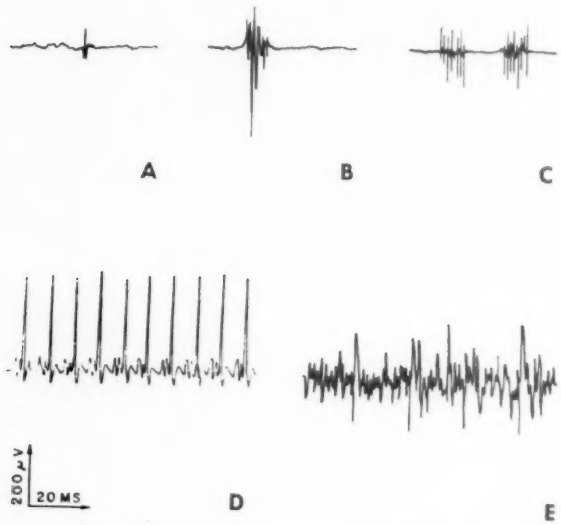

Fig. 3 — Electromyographic findings in muscular dystrophy. *A.* Fibrillation potentials at rest present in seven of 33 patients, more common in amyotonia congenita and in late stages of the progressive dystrophies. *B.* Polyphasic potentials present in 11 of 33 patients, primarily in pseudohypertrophic muscular dystrophy and amyotonia congenita. These are of somewhat shorter duration than the polyphasic potentials typically seen in polio. *C.* Dystrophic potentials found in 30 of 33 patients. *D.* Myotonic potentials found in 11 of 20 patients with pseudohypertrophic muscular dystrophy. Not seen in the other myopathies. *E.* Interferential pattern found after maximal effort and frequently paradoxically after weak effort.

myotonic and the polyphasic, each of which were present in 11 of the 33 patients. There were, however, some characteristic findings in each clinical type of myopathy.

Pseudohypertrophic muscular dystrophy. Of the 20 patients in this group, electrical silence at rest was found in 18 and fibrillation potentials in only two. During voluntary muscle contraction both normal and a variety of abnormal potentials and patterns were elicited. Dystrophic potentials were seen in 19 of the 20 patients, polyphasic activity in eight and giant potentials in only one. Myotonic activity was present in 11 patients and this was the only type of muscular dystrophy in which these potentials were seen. Weak voluntary movement evoked simple patterns in only four and interferential patterns in 16 of the 20 patients (fig. 3*E*). Maximal effort elicited interferential patterns in every instance.

Facio-scapulo-humeral muscular dystrophy. Among four patients with facio-scapulo-humeral type of muscular dystrophy, fibrillation potentials were found at rest in only one. However, dystrophic potentials were found in all four patients. Likewise, as in pseudohypertrophic muscular dystrophy, voluntary attempts at weak movements paradoxically evoked interferential patterns in the most involved muscles.

Amyotonia congenita. In amyotonia congenita, fibrillation potentials at rest were present more frequently than in the other myopathies, being found in four of the nine patients. During voluntary effort, dystrophic potentials were recorded in seven, polyphasic potentials in three and giant potentials in only one patient. In four of these patients, maximal effort evoked only simple patterns, as in patients with polio. In two, minimal effort evoked paradoxical interferential patterns as in muscular dystrophy.

Discussion

Interpretation of the electromyograph involves a consideration of the nature of electrical activity of muscle at rest and during activity. Even though the

electromyograph records the electrical discharge in muscle fibers, impairment in transmission of an impulse in the nerve pathways may cause changes in the pattern of motor unit activity.

In normal muscles at rest, the electromyographic finding is electrical silence. During mild effort, a simple pattern is evoked consisting of isolated or discrete di- or triphasic normal action potentials.[2, 3] When many motor units are recruited by resisted or maximal effort, many action potentials are recorded superimposed on each other so that it is not possible to distinguish individual motor unit potentials. The interferential pattern is composed of normal motor units where the muscle is normal or may include abnormal units in myopathies or neuropathies.

In neurogenic disorders of the upper motor neuron type, the electromyographic findings remain essentially normal, as neither nerve axones nor muscle fibers of the motor unit are involved. In neurogenic disorders of the lower motor neuron type, the primary finding is that of spontaneously occurring fibrillation potentials in muscles at rest and is the result of Wallerian degeneration of the motor nerve axone and subsequent denervation of muscle fibers at the neural pole of the myoneural junction. During early nerve degeneration or regeneration, muscle contraction may produce a variety of polyphasic motor unit potentials, including giant potentials.

In myogenic disorders the primary electromyographic finding is a characteristic change in the parameters of the motor unit potentials — the wave form becomes complex or polyphasic and the duration of these potentials may increase while the amplitude decreases. In severely involved muscles denervation may occur beginning at the muscle pole of the myoneural junction so that fibrillation potentials may be seen. As a result of hyperirritability in the muscle, sustained repetitive myotonic potentials may follow voluntary motion or slight stimuli.[3, 4]

In the present investigation, electromyographic examination of the nine cases of cerebral palsy was compatible with the clinical diagnosis of an upper motor neuron lesion, since electromyographic findings were all normal, indicating the absence of a neuropathy or myopathy.

In the patients with poliomyelitis, the fibrillation potentials found in five of the 11 patients confirmed the presence of denervation of the muscle fibers. The electrical silence at rest which was found in the remaining six patients is assumed to represent uninvolved areas of the muscle. Further confirmation of neuropathic involvement is the finding in 10 of the 11 polio patients of complex or polyphasic motor unit potentials following voluntary movement. Such potentials may be caused by denervation with complete atrophy of involved muscle fibers, leaving many "non-electrical spaces" between the residual uninvolved muscle fibers still capable of generating appreciable electrical potentials. Polyphasicity may also result from disintegration of the action potential due to disturbed transmission to or through degenerating muscle fibers.[5] This results in an asynchronous discharge of the functioning muscle fibers of the remaining motor units. Low amplitude polyphasic potentials resembling dystrophic potentials were also observed in three of the 11 polio patients, presumably due to extreme degeneration of the motor unit complex.

The presence of "giant" motor unit potentials was noted in three of the polio cases. They were usually polyphasic but occasionally biphasic. These potentials usually characteristic of regenerative muscle, may be due to compensatory hypertrophy of the intact muscle fibers or to a high reinnervation ratio of the regenerating muscle fibers.[6]

As a result of the severe and generalized involvement of the polio patients in this study and the resultant great loss of functional muscle mass, the recruitment of motor unit potentials during voluntary effort was found to be considerably reduced. Maximum effort against resistance elicited only a "paradoxical" simple pattern of discharges in 10 of these 11 patients. In the one patient in whom neither fibrillation nor polyphasic potentials were observed, the paradoxical

response of a simple pattern to maximal effort was elicited (polio case 8, table 1).

Polyphasic and/or dystrophic potentials were observed in nearly all the myopathies (31 of 33) and polio cases (10 of 11). In muscular dystrophy, dystrophic potentials were the most common abnormality seen, occurring in 30 of the 33 patients, as compared to polyphasic potentials, which were found in only 11. Although dystrophic potentials are a special form of polyphasic potentials, with the same general wave form characteristics (five or more deflections), they differ in their finer details and in their frequency of occurrence in myopathies as compared to polio. In the myopathies, the dystrophic forms of polyphasic waves are formed by the grouping of thinner, more sparse deflections of a duration of one msec. or less, with a total duration of five to 20 msec. and on the average of lower voltage (50-300 uV). Even the more typical polyphasic potentials seen in muscular dystrophy are, on the average, of lower amplitude, and thinner, more sparsely grouped deflections. On the contrary, the polyphasic potentials of polio sequelae are generally of higher amplitude, thicker deflection, more closely grouped, with a duration of three to 15 msec. and of higher voltage, 50 to 1000 uV. Rodriguez and Oester[3] point out that the individual deflections of dystrophic potentials may resemble fibrillation potentials in configuration and may represent minute surviving elements of the motor unit still under voluntary control.

Giant potentials, which generally reflect regenerative processes, were found in only two of the 33 muscular dystrophies. This is less frequent than their occurrence in poliomyelitis (three of 11 patients). Muscle regeneration in polio is associated with hypertrophy of a potentially normal muscle unit. In muscular dystrophy, however, the regenerative attempt does not reach fruition since all the muscle cells are involved in a progressive degenerative process. Regenerating muscle fibers capable of maximal or giant potentials would therefore be expected to occur in polio more frequently than in muscular dystrophy.

An unexpected finding in muscular dystrophy was the relatively high incidence of myotonic potentials. Previous investigators[7, 8] had reported increased "insertion potentials" and myotonic discharges in pseudohypertrophic muscular dystrophy. After our study was completed there appeared a report by Goodgold and Archibald[9] who also found myotonic potentials in 26 of 36 patients with pseudohypertrophic muscular dystrophy. In our study 11 of the 20 patients (55 per cent) with pseudohypertrophic muscular dystrophy evinced myotonic potentials, indicating increased hyperirritability of the muscle fibers. In none of the other patients, even those with other types of myopathies, were myotonic potentials found. The predilection of myotonic potentials for the pseudohypertrophic muscular dystrophy group may be related to the predilection to muscle hypertrophy characteristic of this myopathy, both clinically and in muscle biopsies and cultures. Myotonic discharges in pseudohypertrophic muscular dystrophy, though present at any age or stage of the condition, were found more frequently during puberty.

The presence of fibrillation potentials has been previously reported in muscular dystrophy.[10] In the present study, fibrillation potentials were seen in seven of the 33 muscular dystrophy patients examined. The significance of these fibrillation potentials is difficult to explain since lower motor neuron involvement is presumably absent in muscular dystrophy. Norris and Chatfield,[11] using a microelectrode technic in patients with muscular dystrophy, observed fibrillatory activity at rest particularly following strong voluntary contraction and especially in less affected muscles. These authors compared these fibrillation potentials to similar changes observed in myotonia dystrophica and attributed them to a state of hyperirritability of the motor nerve fibers in both conditions. Fudema and Oester[12, 13] found fibrillation potentials in rabbits with experimental muscular dystrophy due to avitaminosis E, which were indistinguishable from

denervation fibrillation potentials resulting from nerve section. They surmise that the fibrillation potentials of experimental muscular dystrophy are due to denervation resulting from the separation of intact nerve fibril end plates from degenerating muscle fibers.

In our material, fibrillation potentials were found in only two of the 20 pseudohypertrophic muscular dystrophy patients, and both of these were severely involved (cases 16 and 20, table 1), and both also had myotonic potentials. This indicates that in pseudohypertrophic muscular dystrophy, as in myotonia dystrophica, the presence of both of these potentials might well reflect a state of increased irritability of the muscle fibers, and of a denervation in which the motor unit is involved primarily at the muscle pole. In amyotonia congenita, on the other hand, fibrillation potentials were more common, being present in four of the nine patients, but in no instance did myotonic potentials coexist. This might indicate that the fibrillation potentials in amyotonia congenita may be physiologically different from those of pseudohypertrophic muscular dsytrophy and more like those found in polio where denervation of the motor unit is primarily at the neural pole. There is ample evidence that many patients with amyotonia congenita have histories and pathologic findings suggestive of a prenatal polio, and our electromyographic findings would tend to confirm such a possibility.

Further confirmation of a basic physiologic difference in pseudohypertrophic muscular dystrophy and amyotonia congenita is indicated by a consideration of the nature of the electromyographic response to slight and maximal voluntary effort. In pseudohypertrophic muscular dystrophy, interferential patterns in response to slight voluntary movement were observed in 16 of the 20 patients examined and to maximal effort in all. In no instance in the present study did a simple pattern in response to maximal effort occur, even in the advanced cases.* The inference is that the weakness of the muscle makes such recruitment necessary in order to perform even minimal motor acts. Since in pseudohypertrophic muscular dystrophy, innervation of muscle units is still essentially intact, such synergistic recruitment is possible and is expressed electromyographically as an interferential pattern composed of both normal and abnormal potentials in response to slight voluntary effort. In amyotonia congenita, to the contrary, interferential responses to maximal effort occurred in only five of the nine patients. In the other four, such maximal effort elicited only simple patterns, as was the case in the polio group where 10 of the 11 patients had a paradoxical simple electromyographic response to maximal effort. In only one of the nine patients with amyotonia congenita was an interferential pattern elicited in response to slight effort, similar to the findings in pseudohypertrophic muscular dystrophy. It would thus appear that amyotonia congenita resembled polio more in regard to the *pattern* of response to maximal and weak efforts, and muscular dystrophy more in regard to the *type* of abnormal potential elicited. The group of four facio-scapulo-humeral patients were identical in electromyographic response with the pseudohypertrophic muscular dystrophy group, except for the absence of myotonic potentials.

Electromyographic Classification of Myopathies

It is possible to classify roughly many of the neuromuscular conditions on an electromyographic basis (table 3). Cerebral palsy, like other upper motor neuron lesions, is for practical purposes electromyographically normal. Poliomyelitis on the other hand, is typical of the lower motor neuron lesion, with fibrillation potentials present at rest, and polyphasic and giant potentials during effort. In the severely involved polio with a large loss of muscle mass, there may be an inability to mobilize sufficient

*We have recently encountered several very far advanced pseudohypertrophic muscular dystrophies in which the muscle involvement was so great that only a simple pattern was evinced in response to maximal effort.

Table 3: EMG Classification of Neuromuscular Conditions

	Potentials					Pattern: Effort	
	Fibr.	Poly.	Dyst.	Giant	Myot.	Weak	Maximal
Normal	0	0	0	0	0	S	I
Cerebral Palsy	0	0	0	0	0	S	I
Polio	++	++	+	+	0	S	S
Amyotonia Congenita	++	+	++	+	0	S	IS
Facio-Scapulo-Humeral	+	0	++	0	0	I	I
Pseudohypertrophic	+	+	++	0	++	I	I

S — Simple pattern.
I — Interferential pattern.

muscle units to obtain interferential patterns on maximal effort. Characteristically, therefore, only simple patterns consisting of both normal and abnormal motor unit potentials are elicited on either simple or maximal effort.

The true muscular dystrophies, as characterized by the pseudohypertrophic and facio-scapulo-humeral forms, also have characteristic electromyographic findings consisting of dystrophic and occasional polyphasic potentials during effort. In the far-advanced cases or in the most involved muscles, fibrillation potentials at rest may also be found. The pseudohypertrophic form of muscular dystrophy evinces myotonic potentials in over 50 per cent of the cases. Other than for myotonia congenita (Thomsen's Disease) and myotonia dystrophica of the adult, pseudohypertrophic muscular dystrophy is the only form of muscular dystrophy in which myotonic potentials have been found. Since Thomsen's Disease and myotonica dystrophica are clinically quite distinct from the other progressive myopathies of childhood, the presence of both dystrophic and myotonic potentials in a given patient are strong electromyographic evidence that the diagnosis is pseudohypertrophic muscular dystrophy. In the true muscular dystrophy, voluntary movement is very apt to elicit an interferential pattern regardless of whether the effort is maximal or only slight. This is quite different from the severe polio patient who is unable to enlist such recruitment.

Amyotonia congenita seems to act electromyographically somewhere between a lower motor neuron lesion and a true, progressive muscular dystrophy. Like the muscular dystrophies, there is a high incidence of dystrophic and polyphasic potentials. As in poliomyelitis there is a fairly high frequency of fibrillation potentials at rest. In a given patient with amyotonia congenita, the electromyogram may be characteristically that of a muscular dystrophy, and in another, that of a lower motor neuron lesion. The response to slight and maximal effort in amyotonia congenita may likewise resemble that of either the polio or muscular dystrophy patient. In those who are most severely involved, maximal effort may be incapable of eliciting interferential patterns. In those less severely involved, interferential patterns may be elicited by even minor effort. It is not unlikely that there may be more than one type of amyotonia congenita, one which may be hereditary with a familial predisposition and with or without progressive tendencies, and another which might represent a prenatal myelopathy, resembling polio. Pathologically, patients dying with amyotonia congenita do often have evidence of involvement of the anterior horn cells of the spinal cord.

The electromyographic examination of the patient with muscle weakness has definite value clinically if done by an experienced electromyographer. It is particularly of value in differentiating pseudohypertrophic muscular dystrophy from other myopathies and from neuropathies and in making the diagnosis in early or questionable cases. We consider this procedure much more valuable than

muscle biopsy for diagnostic purposes in patients with early muscular dystrophy. In these early cases electromyography will generally demonstrate the presence of abnormal muscle unit potentials, while the muscle biopsy may still show normal muscle or nonspecific changes.

Summary

An electromyographic study was done on 53 patients with various neuromuscular disabilities:

1. Patients with cerebral palsy were electromyographically normal.

2. Patients with poliomyelitis sequelae demonstrated the typical findings of lower motor neuron lesions, namely fibrillation at rest and primarily polyphasic potentials during effort with an inability to recruit interferential patterns on maximal effort.

3. In pseudohypertrophic muscular dystrophy, dystrophic and polyphasic potentials were most commonly seen during voluntary effort. Myotonic potentials occurred in over one-half of the patients. Fibrillation potentials at rest occasionally occur. It is felt that such fibrillation potentials may represent denervation primarily at the muscle pole as contrasted to the denervation in polio which is primarily at the neural pole. Minimal voluntary effort will generally cause synergistic muscle action with resulting interferential patterns.

4. Facio-scapulo-humeral dystrophy is characterized by electromyographic patterns identical with that of pseudohypertrophic muscular dystrophy except for the absence of myotonic potentials.

5. Amyotonia congenita is characterized by mixed electromyographic patterns, at times similar to that of polio and at times that of muscular dystrophy. No myotonic potentials are present. In some patients maximal effort may elicit only simple patterns and in others minimal effort may elicit interferential patterns.

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special article

An Approach to Biomedical Instrumentation

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● The nature of the subject quantity and the form in which the output data is desired are the primary considerations necessary to specify a measuring instrument system. Such systems are made up of three basic components; an input sensing element to provide a signal proportional to the subject quantity, an output indicator to convert the signal to a scalar deflection, and a modifier to make the sensor signal suitable for the output indicator. The general characteristics and problems peculiar to each of the components are discussed and some basis for their selection suggested.

Until recently, the diagnostician supplemented his own senses and skills in assessing a patient's condition with but a few simple instruments which could usually be carried in his pocket. Similarly, the physiologist depended largely upon the elegantly simple smoked-drum kymograph to record many quantities by the level of liquid manometers or the deflection of levers. In both cases there was very little hardware between the quantities of interest and the senses of the investigator; the measurements or estimates were quite direct, and there was little cause to question that such determinations were reasonably accurate. Today, however, the diagnostician's examining room and the physiologist's laboratory resemble rather closely a radar control center or the transmitter room of a radio station, and, indeed, contain some very similar equipment. This state of affairs has at times resulted in much uncertainty for many of us as to the relationship existing between the output of these indirect and complex measuring systems and the quantity under study.

An ideal measuring system must provide a perfectly accurate indication of the subject quantity. In addition, it must make this accurate measurement without disturbing the subject in any manner. Further, if the quantity of interest is one that changes rapidly with time, the system must be able to follow such changes instantaneously. It is the attempt to fulfill these ideal characteristics that has increased the complexity of measuring instruments.

While accuracy in itself can often be attained by very simple devices, it is the requirement of minimal disturbance to the subject along with rapid response that necessitates the use of delicate sensing elements of small energy output, followed by high degrees of amplification. Such sensitive systems become rather complex in order to limit their response to the desired quantity and to exclude extraneous quantities in the region of the subject or system. In addition, as measurement systems become less direct, increasing attention must be paid to calibration methods. One frequently finds, in bringing a new measuring system into being, that a method that was in principle quite simple and straightforward ends up disappointingly complicated and awkward.

The clinical and laboratory investigator must understand quite clearly the physical principles of his measuring tools, including the step-by-step alterations performed on the signal as it proceeds from the subject to the output device. This is necessary, not only to insure the optimum application and performance, but also because it is his sole responsibility to provide detailed specifications for his instruments, since he alone has the essential knowledge of the characteristics of the subject quantity. While in many cases measuring instruments are complete packages in themselves, often measuring systems are assembled in the laboratory

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from several basic components. For this reason the input and output characteristics of such components also must be familiar if compatible chains are to be connected and the desired results obtained.

The understanding and detailed specification of a measuring system is facilitated by breaking the system down into its several basic components and considering each individually. It is the purpose of this presentation to outline the basic considerations required when planning the instrumentation of an investigation, to review some of the characteristics of instrument components. and to describe a few convenient accessories.

The Measurement Problem

Before designing or assembling a measurement system, two basic questions must be considered: What are the characteristics of the quantity to be measured, and in what form is the output data required?

A. *The Subject or Input Quantity*

1. *Property or variable.* Measurable quantities are of two types: properties and variables.[1] Properties can be measured only by supplying energy to the subject, since properties are, in general, the means by which energy is manipulated. Length, viscosity, thermal capacity, ohmic resistance, and elasticity are all examples of properties. Variables, on the other hand, are forms of energy and may be measured by simply tapping a bit of the energy. Pressure, flow rate, temperature, electric potential, and muscle tension are examples of variables. Thus, to determine electric potential (a variable) a voltmeter is needed, but to determine ohmic resistance (a property) a voltmeter and a known current source are required. In some cases property determinations can be carried out using energy supplied by the subject when both the energy and its manipulation by the property can be sensed.

2. *Magnitude range and polarity.* The range of magnitude of the subject quantity must be estimated in order to specify the required sensitivity and range of linearity of the measurement system. In addition, quantities that have but one polarity are treated differently from those that pass through zero to a reversed polarity. It must be decided whether the absolute magnitude above zero, or only the change or rate of change of magnitude is required. For example, arterial blood pressure shows only one polarity whose magnitude above zero is significant, while arterial flow frequently reverses direction over a portion of the cardiac cycle. It is only the change in magnitude of the potential that is significant in electrocardiography; the magnitude with respect to zero has no meaning. The ballistocardiogram measures the rate of change in position induced by each cardiac thrust.

3. *Frequency spectrum.* The rapidity with which the quantity varies with time and the degree to which these changes must be followed are one of the most important factors in the choice of instrument components, especially the output indicating or recording device. The temporal nature of quantities is most conveniently regarded in terms of the frequency spectrum occupied. The spectral distribution of several typical physiologic quantities is shown in the bar graph of figure 1. While a very wide range of

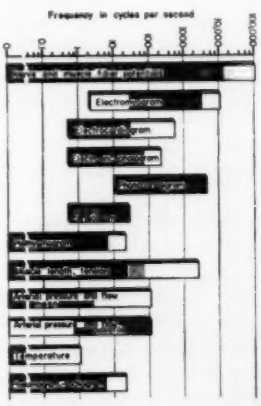

Fig. 1 — The frequency spectra occupied by several quantities of biomedical interest. The shaded areas indicate regions containing the most significant or clinically useful information, while dark bands within these areas indicate frequencies of peak activity.

frequencies is occupied by biologic quantities, it is the lower, sub-audio range from zero to 100 cycles per second, where interest is predominant. The upper frequency limit, which does not cut off as sharply as might be inferred from the figure, is determined by the maximum rate of change of the quantity. The lower frequency limit is likewise determined by the minimum rate of change and extends to zero for those quantities whose sustained magnitude with respect to zero is of significance.

4. *Source impedance.* All measuring processes disturb or load the subject quantity by exchanging energy, and occasionally material, with the subject. This is fundamental to all measurements but is particularly serious in biology due to the exquisite irritability of living material. The degree of disturbance is minimized by permitting only the smallest possible exchange of energy between the sensor and the subject. To realize this condition, the difference between the impedance of the sensor and the source impedance of the subject should be at a maximum and in the proper sense. The source impedance of the subject must be determined in order to properly specify the sensing element. Thus, a liquid manometer, with its moderate volume change with applied pressure, is suitable for determinations of pressure in sources of large capacity, such as the vascular system, but is wholly unsuited for such determinations in small, closed volumes such as the anterior chamber of the eye.

5. *Noise.* The determination of any quantity suffers from interference by the variation of other quantities in the same region. These other quantities of no interest, at least at the moment, are properly termed "noise." The relative magnitude, frequency range, and other qualities of expected noise require as careful consideration as the desired quantity itself, since the measuring system must discriminate between the two. Noise of a much smaller amplitude, of a different quality, or occupying a different portion of the frequency spectrum from the subject quantity may usually be eliminated by careful design of the system. When all three are similar, however, separation of the desired signal from noise may require rather elaborate methods. It is the level of noise remaining after all methods to reduce it to a minimum have been employed, that determines the resolution or maximum sensitivity of the system.

B. *The Output Data*

The most desirable or useful form that the output data is to take is determined largely by the temporal nature of the subject quantity. Quantities that change very slowly and that do not require continuous or prolonged determination are best transcribed from a simple pointer-scale indicator. Rapidly changing quantities in which the amplitude-versus-time waveform is of significance require the use of graphic indicators or recorders. Both methods are quite suitable for use with data which displays significant changes only in long periods measured in minutes. Today there is an unfortunate tendency to use expensive, complex multichannel oscillographic recorders where the more humble, far less expensive, and simpler pointer-scale indicator would suffice. There is much to be said for the elegance and reliability of the hand-plotted chart made by the anesthesiologist during the care of his patient in the operating and recovery room! Other factors in addition to the temporal qualities of the subject quantity also play a role. The method of interpretation to be used, further operations required to aid analysis, and the necessity of storage, etc. all are important. For monitoring purposes, particularly of high frequency phasic phenomena, the cathode ray oscilloscope has no peer. Most output indicators present the data as a deflection or number for visual interpretation. Often, however, the unique discriminating qualities of the ear may be advantageously employed by presenting the data in audible form. Data may be recorded in forms that can be used as inputs to other machines for further manipulation by the use of magnetic wire, tape, or discs, and punched cards or tape. The use of such methods

is quite desirable when large volumes of data must be handled.

The Measurement System

A block diagram of the measurement system is shown in figure 2. It consists of one block representing the subject from which the quantity to be measured is derived, and three blocks to represent the major components of the system, namely the sensor, the modifier, and the indicator. The characteristics of the subject quantity discussed above will determine the type of sensor to be used, and the form in which the data is desired will determine the indicator. The modifier includes the components necessary to transform the output of the sensor into a form appropriate for driving the indicator.

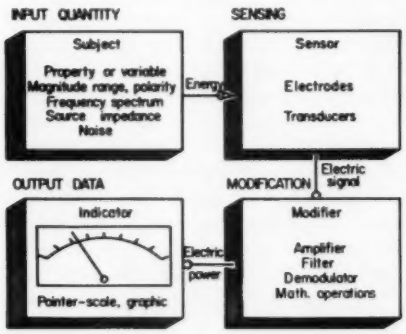

Fig. 2 — Block diagram of the measurement system.

A. *The Sensor*

In general the most difficult of instrument problems centers about the means of sensing the desired quantity. This is due, in part, to the requirement that the sensor cause minimal disturbance of the subject; this, in turn, limits both the size of the sensor and the amount of energy exchanged between it and the subject. Within the constraints of size and available energy, the sensor must provide a signal of usable magnitude, linearly related to the subject magnitude, and must be capable of responding uniformly to all frequency components of the desired quantity, and yet not respond to other variables. Above all, its input-output characteristics must be stable and reproducible. All of these requirements tax the ingenuity of instrument developers to the utmost. It can be said safely that progress in instrumentation is largely dependent upon progress in sensing methods. A number of sensing methods are usually available for a particular subject quantity. The basis of choice centers upon which of the shortcomings peculiar to each can best be tolerated for the conditions at hand.

It is the function of the sensor to single out the particular quantity of interest by providing an electrical output signal which is a function of only that quantity. As indicated in figure 3, sensors fall into two major categories: electrodes and transducers. Electrodes are used where the quantity of interest is either a potential or current *per se* (resting and action potential of nerve, muscle, etc.) or a potential resulting from a transducing process carried out within the subject to determine some non-electric quantity (electromagnetic flowmeter, impedance plethysmography). The larger category of sensing devices is made up of transducers, which, as a class, include all devices that convert energy from one form into another. Sensing transducers used in biomedical instrumentation, however, are almost exclusively of the type which converts its input energy into an electrical output signal.

1. *Electrodes.* Electrodes are divided into three types according to their size, which, in turn, determines their impedance. The largest and most familiar is the type utilized in electrocardiography, electroencephalography, and in some types of electromyography, and may be

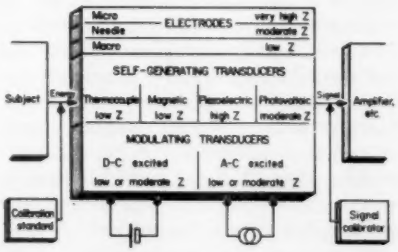

Fig. 3 — Summary diagram showing different classes of sensing elements. Z represents the output impedance of each type.

termed *macroscopic*. They consist of metal plates which are applied to the skin surface with an intervening layer of jelly or paste to minimize resistance and the effects of polarization.[2] The large surface of these electrodes, and the shunting effect of the large bulk of tissue providing the signal, combine to present a rather low impedance, of the order of a few thousand ohms, to the following amplifier. In addition, the signals appearing at the electrodes represent the summation of asynchronous discharges of a large number of individual units which results in a signal in which low frequencies predominate. These two factors, low source impedance and low frequency spectrum, combine to make such measurements quite simple and reliable. This is true despite the fact that the signals are of lower amplitude (a few microvolts to a millivolt or two) than those encountered with smaller electrodes.

Needle electrodes are used where the potentials of interest are derived from a few muscle fibers, a nerve trunk, or a localized area of the central nervous system.[2-4] Due to the much smaller surface area of these electrodes, the impedance seen by the following amplifier is considerably higher (50,000 to 500,000 ohms). The smaller number of units contributing to the electrode potential results in a signal containing a much larger proportion of high frequencies. The signal amplitudes are generally a bit larger than those found with surface electrodes. The higher source impedance and the necessary higher frequency response require a good deal more care in the design of the input circuits to the amplifier with respect to resistance, shunt capacity and shielding. The casual use of long leads or almost any sort of lead shielding, acceptable for electrocardiogram and electroencephalogram recording, would produce severe distortion when used with needle electrodes. Most of these problems can be solved by placing a high impedance preamplifier close to the subject.

The extreme in electrodes is represented by the *microelectrode*.[5-7] This type consists of a submicroscopic glass pipette filled with 0.1 to 3 molar potassium chloride, or a metallic wire drawn down to similar dimensions. The exceedingly small surface area and narrow cross section present a very high impedance to the following amplifier (1 to 50 megohms). The very large advantage of the microelectrode, which has contributed so dramatically to nerve and muscle membrane physiology, is that the potential across the intact membrane of a single cell is determined. With only a single unit discharge contributing to the action potential spike, there is no smearing of the high frequency components and the highest frequencies encountered in biomedical measurements are produced. The absence of shunting by the extracellular fluid allows the determination of the true resting potential (60 to 70 millivolts) and action potential (up to 150 millivolts). The requirements of extreme frequency response (direct current to 30,000-100,000 cycles per second) along with the very high source impedance require extreme care in the design of the following amplifier input and connecting means. Stray capacity of only a few micromicrofarads produces serious distortion due to high frequency attenuation. If attenuation of the signal and disturbances to the cell are to be avoided, the amplifier must feature very high ("electrometer") input impedance and low grid current.

2. *Transducers.* Transducers are required as sensors to measure non-electrical quantities and are specific for each of the forms of energy by which the subject quantity manifests itself. Since a detailed discussion of specific determinations is not the intent of this presentation, the reader is referred to the detailed discussion of transducer methods by K. S. Lion[8] and others.[9,10] Transducers may be divided into self-generating types and modulating types.

(a) *Self-generating transducers.* Self-generating types are those in which all the output energy is provided by the subject and that require no external source of excitation. Four common types of this class are: thermocouples, magnetic devices containing a permanent magnet, piezoelectric crystals, and photo-

voltaic cells. In principle they offer the ultimate in simplicity since connection to a sensitive indicator is sometimes all that is required to complete the measuring system. The *thermocouple,* although requiring a second junction held at a known reference temperature, is still a most useful temperature measuring device that lends itself well to fabrication in even the most modestly equipped laboratory. Its very low source impedance and the predictability and linearity of the potential-versus-temperature relationship contribute to its convenience. *Piezoelectric crystals,* although not suitable for the determination of the sustained component of a pressure or force, can produce useful outputs down to one or two cycles per second by utilizing an amplifier of very high input impedance. *Permanent magnet transducers* find their most frequent application in sensing velocity or acceleration and feature moderate to low output impedance. The *photovoltaic cell,* such as used in the photographic exposure meter, displays a relationship between illumination and its output potential which may be adjusted from near logarithmic to linear by varying the input impedance of the indicator to which it is connected.

(b) *Modulating transducers.* Modulating transducers are those in which the quantity sensed is made to alter either a direct current or alternating current excitation supplied from an external source. The output energy of these transducers comes from the excitation source rather than the subject. In this sense, many transducers are, in themselves, power amplifiers. In all transducers in the modulating class, the output is a function of both the input subject quantity and the excitation, and obviously can be no more reliable or stable than the excitation source. Disregard of this fact has led to disappointment in many systems that were otherwise well designed.

Direct current excited transducers. The output of direct current excited transducers is made proportional to the input quantity by altering the voltage-current relationship of one or more elements. Typical of this class is the *resistance-wire strain gauge* where a pressure, force, or positional change alters the length and diameter of a fine wire and thus its resistance. By causing one or more such elements, connected in bridge fashion, to be altered over a small fraction of their total resistance, an output directly proportional to the subject quantity is obtained. Strain gauges feature very rapid response and high degree of reliability, provided the elastic limits of the elements are not exceeded. Where larger dimensional changes (over a fraction of a millimeter) are to be followed, *resistance elements with moving contacts* are used. By exciting from a high resistance, constant current source, the output potential is linearly related to the resistance. The high temperature coefficient of many resistance materials, while useful for the determination of temperature, can be a source of difficulty. The use of such devices requires temperature compensation of some form. The voltage-current relationship may be altered in accordance with an input by other means; one is through the use of a photoconductive or photoemissive cell. Here the input quantity is made to modulate the quantity of light falling on the cell. Another is through the alteration of the transconductance of a special vacuum tube by the movement of the anode.

Alternating current excited transducers. Several advantages are obtained by using alternating current or carrier excitation. By replacing direct current excitation with alternating current, a much wider variety of transducing methods is made available. In addition, the output alternating current signal is, in many respects, easier to manipulate by the following amplifier. A third advantage is that it provides a method, through the selection of frequency, for the elimination of many troublesome sources of interference. While formerly, A.C. transducer excitation was used primarily to avoid the troublesome drift encountered in high gain D.C. amplification, progress in D.C. amplifier design has made this reason of little importance today. An occasional application of the carrier method is to

translate quantities from one portion of the frequency spectrum to another more suitable for human sensing. Many D.C. transducers may utilize A.C. excitation. By replacing the D.C. supply with A.C., the output becomes an A.C. of amplitude proportional to the input quantity. If the transducer is of a bridge type, it may be balanced so that no output appears when no input is applied, but an input in one direction produces a proportional output of one phase, and an input in the opposite direction results in a proportional output of the opposite phase. On the other hand, some transducers show an A.C. output in the absence of an input, which is then increased by an input of one phase and decreased by an input of the opposite phase, but never goes to or beyond zero. The importance of this differentiation is in the type of demodulation used to convert the A.C. signal to D.C. in order to operate the output indicator or recorder.

The use of A.C. excitation provides a means of transduction based on the broader method of *impedance alteration,* which includes variations of resistance, capacitance, and inductance. By allowing a position change, force, or pressure to alter the distance between a pair of metallic plates, capacitance is altered, thus producing a proportional change in an applied A.C. potential. A similar process can be carried out with a pair of inductances or a movable ferromagnetic core in one or more inductances. Blood pressure gauges of extremely small compliance and excellent high frequency response utilizing the capacitance method have found wide use.[11] A catheter tip manometer for intracardiac pressure recording utilizes an inductive unit of the ratio transformer type.[12]

The transducing process is sometimes carried on *by energy application within the subject* itself. In this method, properties or variables are sensed by supplying energy of known form, such as a current, pressure or magnetic field, and the output signal is sensed by electrodes or another transducer. One form of plethysmography involves the passing of a known current through a length of limb or digit; this results in a voltage drop appearing between a pair of electrodes which is a function of the contained length and diameter.[13] Blood flow velocity may be measured by determining the difference in time for an ultrasound pulse to pass upstream and downstream between two piezoelectric pressure transducers.[14, 15] Another form of blood flowmeter, not requiring vessel incision or sectioning, measures the potential generated on the vessel surface by the stream flowing through a magnetic field. With the field and diameter held constant, the potential is a linear function of the volume rate of flow.[16, 17]

Frequency of A.C. excitation. Several criteria are used to choose the frequency of alternating current excitation, but most important is the frequency range of the input quantity. It is fundamental that the carrier or excitation frequency must be at least twice the highest frequency component in the subject quantity to be recorded. Thus, by using a 60 cycles per second carrier, the highest frequency component of the input quantity recorded by an ideal system would be 30 cycles per second. In practice, however, the carrier frequency must be three to four times the highest input frequency. The use of carrier methods offers a powerful advantage over direct current methods, particularly when the transduction process is carried out within the subject, by allowing the avoidance of regions in the spectrum containing large interfering noise quantities. For example, in the measurement of blood flow by the magnetic method the flow-induced potentials are quite small (microvolts), whereas, those in the region of the heart resulting from cardiac action currents are many times larger (millivolts), and would completely mask the desired flow signal. However, the utilization of an alternating magnetic field of high frequency (about 500 cycles per second) produces a flow signal in a region of the frequency spectrum that is remote from that occupied by the noise. The use of selective carrier amplifiers or proper demodulation and filters allows the complete rejection of otherwise overwhelming noise.[18]

B. *Calibration*

As measurements become less direct through the use of transducers and the interposition of an increasing number of elements between the subject and the output indicating device, the need for calibration methods increases. The absolute calibration of the entire system is usually done by substituting for the subject a source supplying a known quantity to the sensing device. While this should be done frequently between determinations on subjects, a means of checking at least that portion of the system beyond the input sensor during the recording period is quite useful. A simple device for doing this is shown in figure 4 and is based on a method that has become standard practice in both electrocardiography and electroencephalography. This device places a known potential at very low source resistance in series with the electrodes or transducer and the input circuit of the amplifier. By connecting the calibration signal in series with the input sensor two advantages are obtained over a shunt or sensor substitution method. The most important is that the calibration voltage appears at the amplifier input at the same source impedance as the signal from the sensor. Thus, any loading imposed by the amplifier input is the same for both subject and calibration signal, and the true net sensitivity is obtained. This is quite important in those cases where the amplifier or modifier input impedance cannot be sufficiently large to produce insignificant loading. A second advantage is that the calibration can be done at any time without interruption of the recording process, the calibration signal appearing as a jump in the base line by an amount equal to the calibration potential. In the circuit shown (fig. 4), R_1 is a low value of resistance, 100 ohms or less, which is very much smaller than the source impedance of the sensor. In the "D-C CAL" position of the switch, a known voltage drop across R_1 is produced by battery B_1 in series with R_1 and R_2. The stable terminal potential of mercury cells throughout most of their usable life makes them ideal for this application.

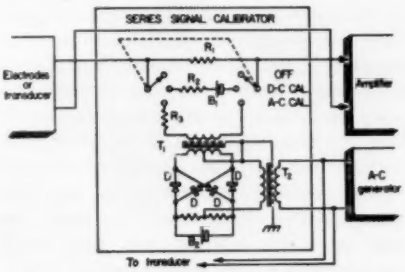

Fig. 4 — A series calibrator suitable for either D.C. or A.C. calibration. Isolation transformers T_1 and T_2 must be well shielded.

In the "A-C CAL" position, the current source is an alternating current derived by switching the polarity of the battery B_2 at the A.C. generator or carrier frequency. The switching process is done by the four diodes, D, connected as a ring modulator whose output magnitude is determined almost completely by the battery potential, provided the switching voltage from the carrier source is at least several volts. The magnitude of the current through R_1 is determined by the stable, passive elements of the transformer T_1 and the sum of R_3 and R_1, and by the battery B_2; but not by the diode characteristics or the magnitude of the A.C. carrier. The A.C. calibration signal produced in this manner is a rectangular wave. In rare cases where this might be undesirable, a tuned circuit between the isolation transformer T_1 and the calibration resistance R_1 can be employed to convert the square wave into a sinusoid.

C. *Signal Modifiers*

To produce minimal disturbances of the subject, the smallest possible amount of energy must be exchanged between the sensor and the subject. This results in sensor outputs of small energy levels. In order to operate most output indicators, the energy level of the signal must be raised many times through the use of amplification. Amplifiers also are used as a basic component in other forms of signal modification including frequency conversion, demodulation, filtering, integrating, differentiating, etc. where power level is not the primary concern.

1. *Amplification.* The most important characteristics of amplifiers are: frequency response, input impedance, output impedance, and gain. In addition, where very small signals are encountered, noise must also be considered. Up until recently amplification depended entirely upon *vacuum tubes,* but today these are being rapidly replaced by *transistors.* It will probably not be too long until vacuum tubes will be used only in a few special cases, particularly where very high input impedances are required. Biologic amplifiers fall into two general classes based on their low frequency response characteristics.[19] Amplifiers that will provide a uniform gain versus frequency down to zero frequency or D.C., are termed "D.C. amplifiers" while those that show a decreasing gain below a certain frequency and have no gain at D.C. are "A.C. amplifiers."

(a) *D.C. amplifiers.* D.C. amplifiers are required for all signals that contain a significant sustained or D.C. component, and are thus used in conjunction with most D.C. excited transducers and such bioelectric measurements as the transmembrane potential using microelectrodes. The largest source of difficulty with D.C. amplifiers is the instability of the output zero level or "drift." Drift arises from a number of sources within the amplifier but is primarily due to changes in parameters of the input stage of the amplifier. Considerable effort has been applied to solving the drift problem, and today, two general schemes are most frequently used. One is to convert the input D.C. signal into an A.C. by a *high speed switch ("chopper" or "breaker").* This is identical in principle to the A.C. excited transducer methods. Mechanical choppers which can switch at rates up to 500 cycles per second introduce very small drifts, and their outputs can then be amplified by A.C. amplifiers that are free of drift. After sufficient amplification, the A.C. is converted back to D.C. by a demodulation method employing synchronous switching by diodes or another chopper. The high frequency response of chopper D.C. amplifiers is limited to a quarter or less of the chopping frequency. While non-mechanical chopping methods using solid-state devices can provide much higher chopping rates, and therefore, higher frequency response, they do not possess sufficient freedom from drift to offer much advantage. A second type of D.C. amplifier is the *"chopper-stabilized" type.* This method utilizes the advantages of the chopper method without the limitation in high frequency response. This type uses a chopper amplifier to amplify the drift or deviation of the output of a direct coupled amplifier and feed it back in a manner that opposes the drift. The chopper amplifier, with its limited high frequency response, need only respond to the slow drift but has no effect on the high frequency response of the main direct coupled amplifier. Thus, today, many fine D.C. amplifiers are available with wide frequency response and drifts down in the microvolt level.

(b) *A.C. amplifiers.* It is not necessary or desirable to utilize D.C. amplification for sensor outputs from A.C. excited transducers or from electrodes sensing signals containing no steady potentials of significance. The use of D.C. response for such quantities as the electroencephalogram, electrocardiogram, or electromyogram would only introduce the spurious responses due to electrode polarization. A.C. amplifiers, however, for most biologic purposes require uniform response down to very low frequencies, and for this reason are of the *capacitance-coupled* rather than transformer-coupled type. D.C. amplifiers may be converted to A.C. types simply by placing a capacitor between the sensor and the amplifier input. It is considered good design practice, where A.C. coupling is desired, to use only one capacitance-coupled stage, the remaining stages being direct coupled. This technic is used to minimize the recovery time from an overloaded state. When several capacitance-coupled stages are connected in tandem and are overloaded by a very large signal, recovery can proceed only one stage at a time and the net recovery time is proportional to the product of the number of stages and the individual coupling time constants. However, when only a single capacitance-coupled stage

is involved, the recovery time constant is identical with the coupling time constant.

(c) *Frequency response.* Except for chopper amplifiers, the upper limit of frequency response is determined by stray shunt capacity. Since electronic amplifiers can easily be constructed with uniform gains from zero to many megacycles, the upper limit of system frequency response is rarely determined by the amplifier, but, in general, is set by either the input sensor or the output indicator. Frequently, however, the amplifier is deliberately restricted in its response to compensate for certain transducer characteristics or to reduce noise.

(d) *Impedance.* For most applications the input impedance of an amplifier should be very much larger than the output impedance of the signal source. For vacuum tube amplifiers input impedances of up to several megohms and 20 to 50 micromicrofarads pose little difficulty. Special design is necessary, however, for such applications as microelectrode amplification where very high resistance and low capacitance are required. Transistor circuitry does not lend itself easily to high input impedance; however, by the use of feedback, transistor amplifiers can be made with input impedances approaching one megohm. Where large interfering signals are apt to be present, as in the case of such bioelectric determinations as electrocardiogram, electromyogram, or electroencephalogram, the use of a differential input, where both input terminals are isolated from the common or ground connection, is required. In this way, large interferences that appear in common to the two input terminals are rejected and only the difference in potential between the two terminals is amplified. For less severe requirements, the simpler single-ended input, in which one of the two input terminals is ground, is satisfactory.

The proper output impedance is determined by the type of load into which the amplifier operates. For maximum power transfer the output impedance and load impedance are made equal. On the other hand, many galvanometers would be excessively damped if connected to a low impedance source, and therefore high output impedance, which provides a current independent of the load, is preferred for these devices. An output impedance much lower than the load is required when the output voltage must be unaltered by the load. The output impedance of an amplifier can be readily adjusted by the use of negative feedback. If the feedback signal is proportional to the output current, the output impedance will be high; if the feedback signal is proportional to the output voltage, the output impedance will be low. By using a combination of the two, the output impedance may be adjusted easily over a very wide range to suit load requirement.

(e) *Gain.* The necessary gain of an amplifier is determined by the required full-scale deflection signal of the output indicator divided by the smallest signal expected from the sensor that must provide the full scale indication. Gain, in itself, poses no problem, since it can be increased without limit by cascading additional stages of amplification. The limit on *usable* gain, however, is set by the noise generated in the early stages of the amplifier and in the subject and sensors. Signals that are masked by noise cannot be made observable by increasing gain, for this simply serves to increase the meaningless, noise-produced deflections. Noise arises from many sources, but the irreducible minimum is set by the thermal agitation in the input signal source. Thermal noise, being perfectly random, contains components at all frequencies. Vacuum tubes and transistors also generate noise of both random and low frequency type. Transistors early acquired the reputation of being far too noisy for low-level, high gain amplifier use. However, present day components and circuits provide transistor amplifiers that are superior to those using vacuum tubes when the signal source impedance is below 10,000 ohms.[20] Signals from sources of higher impedance are still amplified with less noise by employing a vacuum tube input stage. In general, noise is kept to a minimum by restricting

the frequency response to the smallest possible range consistent with the spectral requirements of the subject quantity. Thus, measurements that require a very limited frequency response, such as temperature determinations, can use very narrow-band amplifiers that will reduce noise to a small fraction of that obtained using a frequency response suitable for, say, nerve action potentials.

2. *Demodulation.* The A.C. signal resulting from transducing methods of the A.C. carrier type must be converted into a D.C. voltage or current of magnitude and polarity in proportion to the magnitude and phase of the A.C. signal. This process of conversion or "demodulation" is the reverse of the modulation process. Figure 5 compares two circuits used for this purpose: the half-wave detector and the half-wave, phase-sensitive, discriminator.

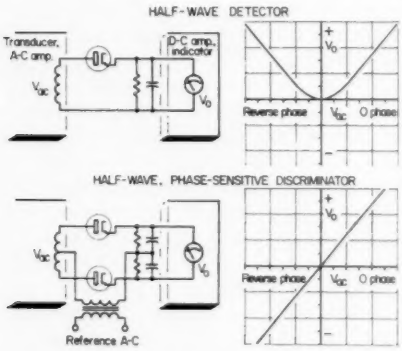

Fig. 5 — Two commonly used demodulators. The linearity and phase sensitivity of the discriminator are not possessed by the simple detector circuit.

The *half-wave detector* is a circuit used commonly in radio receivers and is suitable for this purpose provided the signal is quite large, 10 volts or more, and not of the suppressed carrier type. However, for many of the signals of transducer instruments the shortcomings of this demodulation method are severe, as shown in the accompanying graph. As the A.C. signal approaches zero, the output-versus-input characteristic of the circuit becomes non-linear. Further, this demodulation method cannot detect the reversal of phase in the A.C. signal resulting from a reversal in polarity of the subject quantity. The resulting output can be of only one polarity, and therefore is identical for inputs that are equal but opposite in direction!

Discriminators, on the other hand, are those demodulation circuits that produce an output polarity corresponding to the phase of the input. These circuits use a reference voltage, the same A.C. carrier that excites the transducer, to switch the diodes from conduction to non-conduction. The phase of the signal, relative to that of the reference voltage, determines the output polarity. Since the diodes are switched from full on to full off by the reference voltage, linearity, even at small signal levels, is preserved down to, and through, zero. Two other important advantages are obtained by the use of the discriminator. First, the discriminator modulates low frequency noise to high frequencies where it is eliminated by filters placed between the demodulator and the remaining amplifier-indicator components. The second advantage arises in the ability of the discriminator to reject A.C. components of a frequency equal to the A.C. signal but 90 degrees out of phase. Such components, which can cause serious interference, arise through certain transducing methods (magnetic flowmeter), and through spurious coupling. The failure to use the phase-sensitive discriminator, in one of its many forms, has led to inferior performance in a great many instruments that were otherwise well designed.

3. *Filtering.* Filtering of some form is required to remove carrier components and other modulation products from the output of the demodulator. It frequently happens that the net response of the system must be made as large a fraction as possible of the carrier frequency. While, in principle, this net uniform response cannot exceed half the carrier frequency, careful design can allow a response up to about one-fourth the carrier frequency. This is done by using a filter that will pass all components up to a certain frequency and then produce an increasing attenuation for all frequencies above the cut-off frequency. A simple filter, consisting of a resistance

and capacitance, will produce an attenuation approaching six decibels per octave above cutoff, but use of this method requires that the cut-off frequency must be many octaves below the carrier, severely limiting the net frequency response of the system. Much superior filters using inductances and capacitances can produce attenuations above a cut-off frequency of 60 or more decibels in less than an octave. However, in the range of frequencies occupied by so many of the biologic signals, inductance-capacitance filters are bulky, expensive, and quite subject to pickup of spurious signals. Useful filter circuits, preserving the simplicity of resistance-capacitance filters while minimizing their shortcomings, are described by W. D. Fryer.[21]

4. *Operational amplifiers.* Many signal modifications of high precision are performed through the use of a high gain, D.C., polarity-reversing amplifier called an "operational" amplifier.[22] An example of its use for selecting a narrow range of frequencies out of the low frequency spectrum from 0.5 to 100 cycles per second is shown in figure 6.[23] This process, useful in spectral studies of electroencephalogram and other low frequency signals, is not easily accomplished by conventional tuned-circuit methods. This circuit provides the high degree of selectivity by connecting a twin-T resistance-capacitance filter in the feedback path of the operational amplifier. At the filter null, little feedback occurs, and the amplifier exhibits very high gain, but at other frequencies the filter provides little attenuation and thus reduces the amplifier gain to a low value. By a similar process, using other circuit elements in series with the amplifier input and in the feedback path, such operations as multiplication, addition, differentiation, integration and many others may be accurately performed. Although developed originally for computational use, wide applications of the operational amplifier are found in measuring instruments.[24, 25]

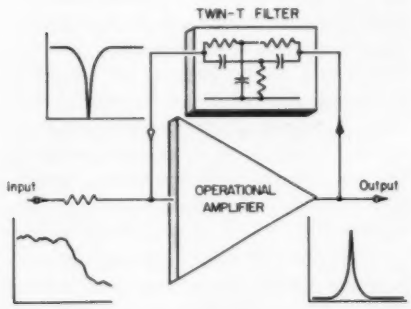

Fig. 6 — A means for selecting a narrow band of frequencies from a low frequency spectrum. The small graphs show a typical amplitude-vs.-frequency plot of an input signal, the transfer characteristics of the twin-T filter in the feedback path, and the resulting net gain-vs. frequency response of the circuit.

D. *Output Indicators*

Output indicators and recording devices are selected primarily on the basis of the temporal nature of the subject quantity.[26] They are properly classed as transducers, in that they convert an electric signal, voltage or current, into a proportional deflection of a pointer or writing element. Since the deflection of a pointer or writing element involves the acceleration of a restrained mass of some form, output transducers show the same sort of frequency limitations that are characteristic of input transducers. Generally speaking, for a given type, the maximum frequency response is inversely proportional to the power sensitivity of the output indicator. There is considerable overlap of the frequency spectrum covered by each type which allows several other characteristics to contribute to the selection of a particular device. Among these are power sensitivity, precision, linearity, recording method, rectilinear or curvilinear coordinates, convenience, cost, etc. It must be admitted that personal taste also plays an important role.

A summary of the suitability of several standard indicating and recording instruments for signals occupying various regions of the spectrum is shown in the bar graph of figure 7.

1. *Sensitive light-beam galvanometer.* The light-beam galvanometer represents the most sensitive of the common indicating devices used today. It is frequently incorporated in instruments using photocells as input transducers,

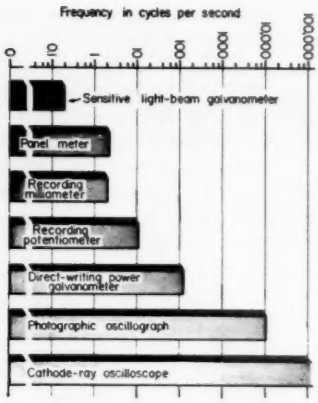

Fig. 7 — The frequency spectra covered by several commonly used output indicators and recorders. The limit for the cathode-ray oscilloscope is not shown, but can extend to hundreds of megacycles.

such as photofluorimeters, spectrophotometers, and ear oximeters. Its very high sensitivity, as high as millimicroamperes per division, permits its deflection by the photocell output without the need for amplification. The deflection of a light beam focused on a ground glass scale is produced by a mirror attached to a moving coil suspended between the poles of a permanent magnet. The very high sensitivity is achieved by the combination of a large number of turns on the coil, small restraining force in the suspension, and the use of a relatively long light beam lever. The small restraining force, along with the mass of the coil and mirror, result in a rather long natural period in range of one to five seconds. Damping is determined almost entirely by the external circuit resistance which must be adjusted carefully if the fastest response with minimum overshoot is to be obtained. While the inherent slow response limits the use of the device to quantities that do not show considerable change from minute to minute, the very high sensitivity offers a considerable advantage in producing a simple measuring system.

2. *Panel meter.* The moving-coil deflection of a pointer over a scale, typified by the common panel meter, is used to indicate current in the range of 10 microamperes up to many amperes, or, with a series resistance, from about 50 millivolts up to several thousand volts. The coil is suspended on a pivot between jeweled bearings and restrained at the zero position by hair springs. A very wide variety as to quality and range is available. Such instruments of the laboratory type are available with accuracies of 0.1 per cent; less expensive ones have only three to five per cent accuracy. In general, the response is considerably faster than that of the light beam type, many producing a full scale response in a tenth of a second. While the more sensitive types can, in some cases, be deflected directly by transducers, panel instruments are usually used to indicate the output current or voltage of an amplifier and to monitor operating conditions within instrument components.

3. *Recording milliammeter.* The recording milliammeter uses a moving coil element similar to that in the panel meter, but with the pointer replaced by a pen. The friction of the writing pen limits the maximum full scale sensitivity to the order of one to five milliamperes, and the mass of the coil and pen limits the frequency response to about one cycle per second. Chart widths of approximately five inches are typical. The ordinate may be curved about the radius of the pen or made linear by a suitable linkage. Friction can be reduced by using the dotted trace of a pen spaced away from the chart but pulled intermittently to the chart surface. This system provides a simple recording means of quite modest cost. The comparatively high sensitivity with the direct writing feature, makes the recording milliammeter one of the simplest of recording means for low frequency quantities. The use of capillary pens, that must be carefully balanced to insure minimum friction, occasionally introduces trouble unless considerable care is used in the maintenance of the inking system.

4. *Recording potentiometer.* The recording potentiometer represents one of the most refined methods available for recording low frequency signals. These excellent instruments have received far less attention in the biologic and medical instrumentation field than they deserve. They are a true potentiometer maintained

automatically at balance by a servo system actuated by an error signal proportional to the departure from true balance. When at balance, they present no load to the driving system. A precision slidewire provides an accurate and linear voltage drop from a stable current source which, in many instruments, is periodically compared to a standard cell. The moving contact, carrying the recording pen, is driven along the slidewire by a motor whose current is supplied by the amplified difference between the input signal and potential drop along the slidewire to the moving contact. This provides a method which allows accuracies and linearities to be achieved within 0.25 per cent. The standard form of the instrument utilizes full-scale deflections of 10 to 11 inches. Full-scale sensitivities range from as small as 0.25 millivolt up to 100 millivolts. The response time for full-scale deflection is usually of the order of one second, but high speed models with 0.25 second response are available. Such recorders will allow a uniform frequency response for two inch peak-to-peak deflections of nearly 10 cycles per second. In recent times a number of recorders of this type, but less expensive and somewhat less accurate, have appeared on the market. For multiple channel recording, intermittent printing of a symbol for each of up to 24 inputs at five to 30 second intervals is used. Two pen recorders allow continuous, simultaneous recording of two inputs. While no loading upon the input source is produced at balance, the maximum response speed and minimum error are obtained when supplied from sources of 30,000 ohms or less.

5. *Direct-writing power galvanometer.* By far the most popular recording method used in medical instrumentation is the "direct-writer" power galvanometer typified by that used in most modern electrocardiograph machines. The basic element is still the moving coil galvanometer, but to provide fast response and overcome friction a very stiff restraining spring and heavy wire coil are used. The power requirements for deflection are many times that of other moving-coil devices and therefore a power amplifier is always used to drive such recorders, and indeed, is usually considered an integral part of this recording device. The sensitivity then, is usually dependent upon the amount of amplification supplied as a part of the recording unit. The frequency range of uniform response extends from zero to 50 cycles per second, but some units claim responses of well over 100 cycles per second. The maximum full-scale deflection is limited to five to eight centimeters by the length of the writing arm, which must remain fairly short if high frequency response is to be obtained. Writing by ink pens, or heated styluses on plastic coated paper, is most frequently used. While the advantage of ruggedness, fairly fast response and immediate availability of the finished record contribute to the usefulness of this recording method, limited accuracy and resolution along with the temptation to use them to record rapidly changing quantities beyond their range of uniform response, are serious drawbacks in their use as a universal recorder.

6. *Photographic oscillograph.* The closest approach to a universal recording means is the photographic oscillograph. A light beam, focused on moving photosensitive paper or film, is deflected by a mirror galvanometer of the moving coil or bifilar type. The nearly universal application of this recording means arises from the wide range of available galvanometers. Galvanometers are available that permit recording signal frequencies as high as 10,000 cycles per second from high current sources on the one hand, and that have sensitivities in the range of five to 10 mm. deflection per microampere at 20 cycles per second on the other. Eight to 36 channels may be recorded in overlapping traces on charts six to 12 inches wide, with each channel utilizing the full chart width if desired. Linear coordinates and channel-to-channel ordinate alignment are precisely obtained. Up until the last few years, the greatest disadvantage of the photographic oscillograph, and the chief reason it had not found widespread use, was the requirement of darkroom processing of the record before the results could be observed. However, this has

been largely overcome by rapid development processes that can be carried out in an accessory unit, or within the oscillograph itself. Thus, if one can accept the delay of a few seconds the advantages of direct writing systems can be obtained along with the wide range of frequency response and sensitivity.

7. *Chart speed.* The chart speed is an important consideration in all recording instruments. While a single chart speed is standard for some routine determinations, such as the clinical electrocardiogram, a range of speeds is usually desired for multi-purpose research application. Constant and reproducible speed is produced by the use of synchronous or governor-controlled motors, with the final speed adjusted through belt or gear reduction units. The maximum useful chart speed is indicated by the maximum response frequency of the deflecting method and is of the order of a few millimeters per second per cycle response. While this maximum speed is usually provided by the manufacturer, sufficiently slow speeds are too often unavailable. It is often desired to use a particular recorder over a range from centimeters per second to centimeters per hour. In all fairness, however, the lack of such an extreme range is not entirely due to oversight on the part of instrument makers, but often results from technical difficulties in producing a satisfactory trace over such a range.

8. *Cathode-ray oscilloscope.* The cathode-ray oscilloscope can provide a graphic display of electrical events occurring anywhere in the frequency spectrum from zero to hundreds of megacycles. For this reason it is, in many respects, the universal output indicator. The indication is produced by a beam of electrons focused on a phosphorescent screen. The beam, which has no mass of consequence, is deflected by either an electrostatic or electromagnetic field produced by the amplified input signal. The beam is deflected in the vertical, or ordinate, direction in proportion to the magnitude of the input signal. In order to display the input signal graphically versus time, the beam is also deflected horizontally at a uniform, known rate in a repetitive fashion. This deflection, termed the "time-base" or "sweep," corresponds to the chart speed of recording instruments and should range from one or more seconds per centimeter to 0.1 millisecond per centimeter. In order that slowly changing variables at slow sweep rates may leave a visible trace, rather than appearing as simply a moving spot, screen phosphors of several seconds persistence, of the P2 or P7 type, are used. Multiple traces can be produced by multiple-beam cathode-ray tubes, or by rapidly switching the deflection system between two or more inputs. Three and five-inch diameter screens are most frequently used; however, large-screen, multichannel instruments are available for operating room or classroom display. Oscilloscopes for biologic and medical purposes must respond from D.C. but need not extend much higher than 100,000 cycles per second. The deflection sensitivity of the more commonly used electrostatic cathode-ray tubes is of the order of 50 to 100 volts per inch, and therefore considerable voltage amplification of most signals is required. The input sensitivity, including the contained amplifiers, is usually in the range of 50 microvolts to 100 millivolts per centimeter deflection. The cathode-ray oscilloscope is the most frequently used means to visualize the faster bioelectric phenomena, such as the transmembrane action potentials using microelectrodes, and electromyograms and neurograms using needle electrodes. In addition, this system is used to supplement the recording of the electrocardiogram, electroencephalogram, etc. for both diagnostic and monitoring purposes. The oscilloscope is also used to display an X-Y plot of rapidly changing variables as the electrocardiogram in the form of the vectorcardiogram. Recording from the screen is done photographically by either a snapshot of a single sweep or by the use of a moving film upon which only the vertical deflections of the beam are photographed.

9. *Other output recording and display methods.* The use of magnetic tape as a recording means has proved useful

for several reasons. The chief among these is that the information so recorded is always available as an electric signal for later study or manipulation. In addition, by recording and playing back at different speeds, the time scale of the original events can be altered to facilitate interpretation or data reduction. In order to record D.C. and low frequency signals, frequency translation of some form is required. This is usually provided as an integral part of commercial instruments designed for data recording.

Many methods of indication and recording, used in biomedical instrumentation, have not been mentioned in this brief review. Those discussed, however, are typical of the most frequently used methods and encompass problems general to virtually all output systems. In addition to these are digital indicators that present a number in lieu of a pointer deflection and digital recorders that produce punched cards, tape, or printed numbers. Such devices are used to aid in the reduction of data by automatic sorting or to allow its further manipulation by digital computers. In addition, the presentation of some information in an audible fashion in addition to, or in place of, visual indication, offers some distinct advantages. In many respects the discriminating ability of the ear exceeds that of the eye. The use of the audio interpretation of electromyograms has been strongly recommended.

Conclusion

While instrumental measurement methods are based on physical laws and are best discussed in rigorous terms, it must be admitted by even the most sophisticated that considerable intuition and art are involved. Many fine instruments and methods simply will not perform well in the hands of some investigators who find other methods of equal complexity quite satisfactory. This is no doubt due, in part, to the fact that many of us are not trained in areas basic to instrument technology, nor have we taken the time and effort to understand fully many of the systems we are using or that have been suggested to us. More important, however, is the fact that all measurement methods involve finite, and often severe, disturbances to the subject under study, thus necessitating compromises of various sorts. Many methods are, in themselves, quite accurate but so seriously load the subject, or otherwise irritate or stimulate it, that the results have little meaning with respect to the original question. The art in instrumentation primarily is involved in making the correct choices among compromises that best suit the total investigation. Many of the methodologic controversies are simply based on the fact that where one investigator is willing to compromise, another is not. An orderly consideration, however, of each of the basic components of the total measurement system, in a manner similar to that outlined, will be helpful in objectively assembling a system of adequate performance.

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Information relative to securing reprints of this study may be had by checking the Reader Service column on page iv of this issue.

If you do not think about the future, you cannot have one.

— JOHN GALSWORTHY

Study of Growth Patterns in Cerebral Palsy

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● The heights and weights of 86 cerebral palsied children have been measured and found to be significantly below the accepted standards for American school children and below that of an unselected clinic population matched with the patient group in relation to age and ethnic background. Followup measurements one year later, and a more complete anthropometric study including bone-age estimation and determination of proportions of body parts have been done on 50 of these patients. Correlation of growth deviations with degree of clinical disability and with intelligence is presented. Factors affecting growth in brain-damaged children and the relationship between the magnitude of neuromuscular involvement and the amount of growth impairment are discussed.

Cerebral palsy may be defined as impairment of motor function due to intracranial abnormality in the growing child. It encompasses a group of children with evidence of brain damage recognizable on physical examination. Brain damage long has been incriminated as a cause of interference with normal growth as well as development, but little is known about the nature of this influence.

Growth in children in determined by a variety of influences including ethnic, familial, nutritional, and endocrine factors. Therefore, wide variation in body size exists normally at any particular age. Because of this, it is difficult to identify the individual child with growth failure by a single measurement unless extreme deviation is present. Optimally, a longitudinal study would be most valuable in evaluating growth.

As a preliminary to a more comprehensive evaluation of growth factors in brain damage, physical measurements were made of a group of 86 cerebral palsied children, and correlated with their clinical status. To test the applicability of the norms used, in view of our ethnically mixed population, we measured a matched non-handicapped group of children also.

Of the patient group, 35 were inpatients at the Bird S. Coler Hospital Children's Rehabilitation Unit, and the remaining 51 came from a school, an out-patient clinic, and a summer camp. The control group came from routine check-up visits in a pediatrician's office. They were matched with the patient group as to age within two months, ethnic origin, and sex. Each group consisted of 42 males, 44 females, ranging in age from five to 18 years. In each group, 64 were white, 10 were Negro, and 12 were Puerto Rican.

Heights were measured in the standing position where possible, feet together and head held so that the outer angle of the eye was on a horizontal line with the external auditory meatus.[1] These measurements were made to the nearest quarter inch. In children with severe hip and knee contractures, a discrepancy of up to two inches existed between standing and lying heights. Postural abnormalities and scoliosis were added problems. Because of this, it was necessary in a few cases to measure along the body contours with a tape from the greater trochanter to the lateral condyle of the femur and then to the external malleolus because of the inability of the child to lie flat. These compromises introduced an unavoidable error, always in the direction of increasing the apparent stature of the child. Where there was inequality of leg length, the pelvis was leveled so that the length

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of the longer extremity was utilized for the final body measurement. Standing heights were acceptable in 58 of the 86 children. Weights were measured using a balance, with the patient wearing light clothing and without shoes. Clinical data was collected from charts and school records, and diagnoses confirmed by clinical examination.

Heights and weights of all children, both normal and cerebral palsied, then were calculated in standard deviations, using the date modified from Simmons as given in Watson and Lowrey's textbook on Growth and Development in Children.[1] Chi square tests were done on all data when comparisons were made.

Since about 95 per cent of a normally distributed population lies between −2 and +2 standard deviations, −2 standard deviation was taken as the line of demarcation between "normal" and "abnormal" in evaluating data.

Results

1. *Comparison of Raw Heights and Weights.* Seventy-two of the cerebral palsied group were shorter than their matches, and only 14 were taller. Sixty-seven of the cerebral palsied group were lighter than their matches, while 19 were heavier. This was significant in demonstrating an appreciable difference between our patients and the normal group at p equals .005 level for both height and weight.

2. *Heights and Weights of the Normal Group (fig. 1, 2).* Because of the varied ethnic backgrounds in our group, and particularly because of the presence of Puerto Rican children, for whom norms were unavailable,[2-5] we attempted to determine whether the norms used would apply to a non-handicapped New York population of similar social and ethnic origin.

The standard deviations for height of the matched normal patients, as calculated from Simmons' data, were tested against a normal distribution curve and found not to differ significantly. We felt more satisfied, therefore, that these norms provided a roughly adequate standard for testing our cerebral palsied patients (table 1A). Figures for standard deviations of weights of our matched normals again did not differ significantly from a normal distribution (table 1B).

3. *Comparison of Heights and Weights Expressed in Standard Deviations.* When each height in the cerebral palsied group was calculated as a standard deviation, we found that 45 of the 86 cerebral palsied children fell below 2

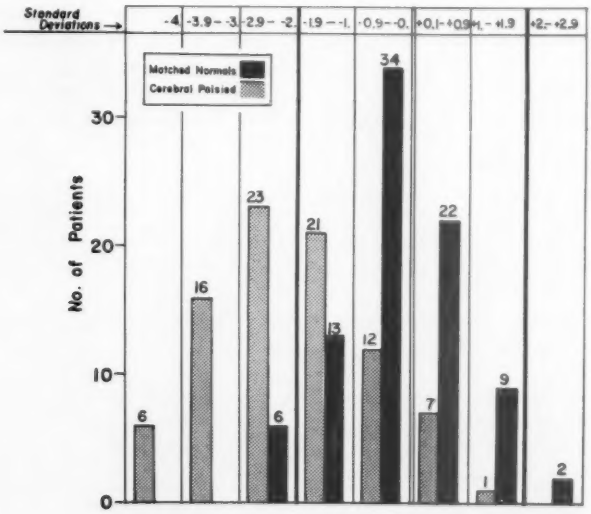

Fig. 1 — Heights expressed in standard deviations.

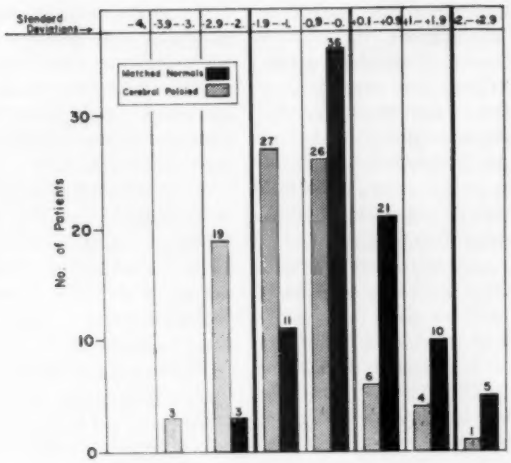

Fig. 2 — Weights expressed in standard deviations.

Table 1: Statistical Evaluation of Results: Test of Matched Group against a Normal Curve

Standard deviations of heights and weights of a group of normal children matched with the cerebral palsied group as to age, sex, and ethnic origin, were tested against a normal distribution.

A. Height

Standard Deviations	Below −1	−1 to 0	0 to +1	+1 and above
Theoretical %	16%	34%	34%	16%
Theoretical Distribution when N equals 86	14	29	29	14
Observed Distribution	19	34	22	11
Chi^2 equals	$\frac{(14-19)^2}{14}$	$+\frac{(29-34)^2}{29}$	$+\frac{(29-22)^2}{29}$	$+\frac{(14-11)^2}{14}$

Chi^2 equals 4.97; p lies between 0.25 and 0.1. Therefore observed distribution of heights of matched normal patients does not differ significantly from the theoretical.

B. Weight

Standard Deviations	Below −1	−1 to 0	0 to +1	+1 and above
Theoretical %	16%	34%	34%	16%
Theoretical Distribution when N equals 86	14	29	29	14
Observed Distribution	14	36	21	15
Chi^2 equals	$\frac{(14-14)^2}{14}$	$+\frac{(29-36)^2}{29}$	$+\frac{(29-21)^2}{29}$	$+\frac{(14-15)^2}{14}$

Chi^2 equals 3.43; p. lies between 0.25 and 0.5. Therefore observed distribution of weights of matched normal patients does not differ significantly from the theoretical.

standard deviations from the mean for their respective age and sex (fig. 1). Of these, 16 were beyond 3 standard deviations, and six patients were more than 4 standard deviations from the mean. In the matched normal group, only six children fell below 2 standard deviations, and none beyond 3. As noted above, this was not a statistically significant difference from a normal distribution.

When weights were expressed in standard deviations, 22 of the cerebral palsied children fell below 2 standard deviations, while only three of the normal children were more than 2 standard deviations underweight (fig. 2).

4. *Height Correlated with Weight.* In the cerebral palsied group, 25 children fell into the same standard deviation for height as well as weight, compared with 42 of the matches, while 52 deviated further below the norm in height than in weight, compared with 28 of the controls. Thus, stature in general was more impaired than weight.

5. *Relationship to Diagnosis (tables 2, 3).* By having the data expressed in terms of standard deviations, we were able to explore the relationship between degree of deviation from the norm, and various aspects of the clinical status of the patient group.

There were 54 spastic, 10 athetoid, 16 mixed, four ataxic patients in the group[6] (table 2). Thirty-five children were quadriplegic, 28 diplegic, and 17 were

Table 2: Diagnosis Related to Height Expressed in Standard Deviations

Diagnosis	Total No. of Cases	Height in Standard Deviations							
		Less than −4	−3.9 to −3	−2.9 to −2	−1.9 to −1	−0.9 to 0	+0.1 to 0.9	+1 to 1.9	+2 to 2.9
Spastic Quadriplegia	9	2	2	2	2	1			
Athetoid Quadriplegia	10	1	1	4	3	1			
Mixed Quadriplegia	12	3	3	3	1	2			
Ataxic Quadriplegia	4			1	1	1	1		
Spastic Diplegia	22		5	8	5	4			
Mixed Diplegia	4		2	1	1				
Atonic Diplegia	2		1	1					
Spastic Paraplegia	4		1	1	2				
Spastic Triplegia	2				2				
Spastic Hemiplegia	17		1	2	4	3	6	1	
Total	86	6	16	23	21	12	7	1	

Table 3: Diagnosis Related to Weight Expressed in Standard Deviations

Diagnosis	Total No. of Cases	Weight in Standard Deviations							
		Less than −4	−3.9 to −3	−2.9 to −2	−1.9 to −1	−0.9 to 0	+0.1 to 0.9	+1 to 1.9	+2 to 2.9
Spastic Quadriplegia	9		1	3	1	2	2		
Athetoid Quadriplegia	10		1	3	5		1		
Mixed Quadriplegia	12		1	6	4	1			
Ataxic Quadriplegia	4				1	2		1	
Spastic Diplegia	22			5	5	9	2	1	
Mixed Diplegia	4			1		2	1		
Atonic Diplegia	2				1	1			
Spastic Paraplegia	4				2	2			
Spastic Triplegia	2				2				
Spastic Hemiplegia	17			1	6	7		2	1
Total	86	0	3	19	27	26	6	4	1

hemiplegic. All six children, who were markedly dwarfed, i.e., below 4 standard deviations in height, were quadriplegic. Fourteen of the 17 hemiplegic children fell within the "normal" range (between −2 and +2 standard deviations), and they comprised seven of the eight children whose heights were above the mean. Weights (table 3), charted according to diagnosis, showed scattered results, but again the hemiplegic children fell substantially within the normal range, only one being below 2 standard deviations.

6. *Relation to Handicap (fig. 3).* We attempted to explore whether the children shortest in stature for their age and sex, also had greater amounts of handicap. A child was considered dependent in ambulation if he used a wheelchair during the greater part of his day, or had to depend on another individual to support him. He was considered independent if he got about on his own habitually, regardless of whether he used appliances. He was considered dependent in feeding if he had to be fed by another person.

Dependence in ambulation correlated significantly with severity of deviation in stature. Twenty-three of 34 children dependent in ambulation had heights below 2 standard deviations, while only 22 of 52 children independent with or without bracing, had statures below 2 standard deviations. This was significant at a p value of less than 0.05.

Similarly, the correlation between dependency in feeding and deviation in height was significant at p equals .02 level. Sixteen of 21 children dependent in feeding had heights below 2 standard deviations, compared with 29 of 65 children who were independent in feeding.

7. *Relationship to Intelligence Quotient.* Thirty-four patients had intelligence quotients above 70; 29 between 50 and 70, and 23 below 50. Sixteen of 23 children with the lowest intelligence quotient had heights below 2 standard deviations, while 29 of 63 children with intelligence quotients above 50 had heights below 2 standard deviations. This was not significant statistically, nor was there statistical significance obtained when the group with intelligence quotients above 70 was compared with the below 70 group.[7]

Discussion

This study helps to substantiate the previously held impression that chronic central nervous system disability has an adverse effect on growth.[8] Sterling[9] measured a group of 100 cerebral palsied children and found similarly that 69 patients ranked below the 10th percentile in height, and 62 below the 10th percentile in weight. He noted that only four of 35 siblings of his patients had heights and only five had weights below the 30th percentile.

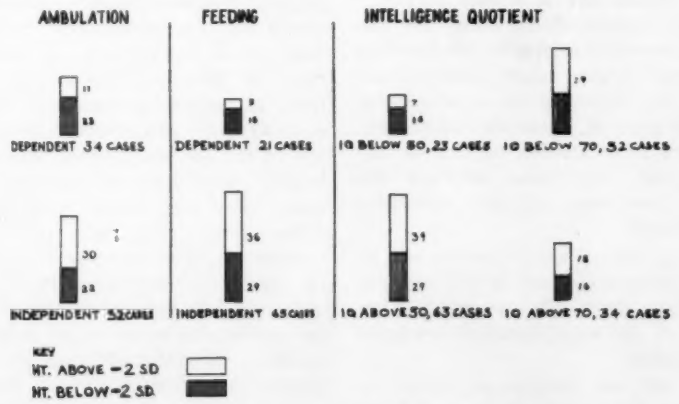

Fig. 3 — Growth patterns in cerebral palsy (86 cases). Relationship between severity of deviation in stature and amount of handicap.

We found that the severity of physical involvement correlated with the degree of impairment in growth. We noted that the children with the shortest statures were quadriplegic, while the hemiplegic children, as a group, fared better. Severe deviation in stature was associated with dependency in feeding and ambulation but showed no relationship to intelligence quotient.

Data was unavailable to distinguish in our group between cases with disability due to prenatal or natal causes, and those due to post-natal factors. However, all the children had been diagnosed as cerebral palsied by 18 months of age. Sterling noted less effect on stature and weight in his six patients whose brain damage was acquired after the age of one year.

We found that prematurity, per se, was not related to height or weight in this group. In Dann's study,[10] the majority of prematures without handicap "caught up" in stature at about four years, although great variation exists.[11] Eighteen of 67 of our patients about whom we had data, had birth weights below five pounds but they possessed no greater impairment of their stature than those of higher birth weight.

There was no relationship between age and severity of deviation in stature, although this point could be clarified by continued measurements to determine whether growth spurts are lacking, or whether growth depression is more likely at a particular period in life. Dutton,[12] studying mongoloid children, for example, showed that despite the fact that they possess a generalized constitutional abnormality involving all organ systems, they still grow at a smooth rate to their shortened adult stature, so that at any one period they have achieved the normal percentage of their predicted adult height.

In our one-year followup of 25 cerebral palsied patients, to date we have noted that all except two children remained in the same standard deviation as previously.

The role of nutritional intake in impairing the growth of these children is unknown. Chewing and swallowing difficulties, as well as inability to self-feed, create feeding problems. Phelps[13] notes clinically that athetoid children consume a greater amount of food because of the increased energy expenditure. In the often more sedentary spastic children, obesity is common. Peek[14] found diets markedly deficient in two-thirds of a group studied by means of questionnaires. Indeed, what constitutes an adequate intake for children with abnormal motility or muscle tone? This poses a frequent problem clinically.

Normal motor activity and muscle tone are considered essential for normal long bone growth. In our group, impairment in stature was equally severe in the 23 children who did no walking, whether or not standing was practiced. The question arises whether lack of physical activity is the major factor in impairing stature, or whether, in central nervous system involvement, abnormal neural stimulation affects growth with no relation to motility.

Periodic followup of the growth rate of a group of cerebral palsied children over a period of time, now under way in our department, along with records of activity, developmental changes, and nutrition, should help to provide clues concerning the influence of the central nervous system in physical growth.

Summary

Heights and weights of 86 cerebral palsied children were measured and found to be significantly below the norms used, and significantly lower than those of 86 non-handicapped children from the same geographic area, matched as to age, sex, and ethnic origin. Forty-five of the cerebral palsied patients had heights more than two standard deviations below the mean. Depression of stature was associated with greater severity of involvement as measured by the number of extremities involved, the ability to self-feed and to ambulate, but not significantly related to the intelligence quotient. Factors affecting growth in cerebral palsied children were discussed.

Acknowledgment: Charles Tramont, B.S., provided technical assistance in this study.

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editorial

The Physiatrist Looks at Law Science

Medical jurisprudence, or legal medicine, is that branch of knowledge which applies the science of medicine to the service and administration of the law. In medical jurisprudence, medicine deals with the interaction of forces involving the body, both within and without. Law deals with the relationships between individuals and groups of persons. The importance of personal injury cases, in terms of doctors, lawyers and economics, is indicated by the fact that 70 percent of all cases appearing in federal and state courts are made up of personal injury litigation. The physiatrist, by virtue of his special training, is able to cope with the major medical problems inherent in personal injury.

In neuromusculoskeletal disease the evaluation of the role of trauma producing a primary disturbance or an aggravation of a preexisting condition, and the extent and prognosis of the disease require expert medical judgment.

In the medico-legal field several movements recently have developed such as Law Science led by Dr. Hubert Winston Smith, a brilliant trial lawyer and physician, the National Association of Compensating Claimant Attorneys, and the American Academy of Forensic Science.

The merits of each movement need not be discussed here but the prime purpose of each is to sponsor postgraduate courses in which participating physicians and lawyers instruct attorneys in recent medical and legal developments. Similar movements are being developed rapidly at medical schools and in lawyer-doctor groups. Many joint ventures, such as those sponsored by the Legal and Socioeconomic Division of the American Medical Association, the American Bar Association, and by corresponding state associations, are being conducted currently throughout the country. The Law Science Academy of America has held extensive seminars in which leading medical and legal personnel have participated. In like fashion, the American Academy of Forensic Sciences teaches lawyers more about medical science and doctors more about legal processes than either discipline would ordinarily learn without special effort.

The physiatrist, by virtue of his scientific background in neuromuscular and musculoskeletal disease both from the standpoint of diagnosis and of rehabilitative medicine, assists in the formulation of accurate and demonstrable information for legal

judgment. Electrical recording devices for electromyography, oximetry, pulmonary ventilation studies and low voltage testing, activities of daily living evaluation, manual and mechanical muscle testing, and range of motion determinations make it possible to evaluate objectively data necessary for a just appraisal and disposition of personal injury claims. Not only does the physiatrist minimize the problem of permanent disability, he evaluates the degree of permanent impairment. By the use of special skills to evaluate the disability a more equitable award can be made for loss of neuromusculoskeletal function.

In personal injury problems, therefore, the physiatrist functions at more than one level; he clarifies the physical impairment and he helps the lawyer formulate an equitable evaluation of the medical problem. In the evaluation the physiatrist can show how the disability can be reduced in incapacitated persons. In Michigan, for example, workmen's compensation laws are being modified so that vocational rehabilitation is made part of any future award to the patient. This makes for a more complete as well as a more realistic approach to medical and vocational rehabilitation. In some states impartial boards of medical experts have been established with the physiatrist participating at the top level in such determinations.

— Max Karl Newman, M.D.

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